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Application of Inorganic Membrane Technology To Hydrogen–hydrocarbon Separations

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APPLICATION OF INORGANIC MEMBRANE TECHNOLOGY TO HYDROGEN–HYDROCARBON SEPARATIONS

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ABSTRACT

Separation efficiency for hydrogen/light hydrocarbon mixtures was examined for three inorganic membranes. Five binary gas mixtures were used in this study: H_2/CH_4 , H_2/C_2H_6, H_2/C_3H_8, He/CO_2, and He/Ar. The membranes examined were produced during a development program at the Inorganic Membrane Technology Laboratory in Oak Ridge and provided to us for this testing. One membrane was a (relatively) large-pore-diameter Knudsen membrane, and the other two had much smaller pore sizes. Observed separation efficiencies were generally lower than Knudsen separation but, for the small-pore membranes, were strongly dependent on temperature, pressure, and gas mixture, with the most condensable gases showing the strongest effect. This finding suggests that the separation is strongly influenced by surface effects (i.e., adsorption and diffusion), which enhance the transport of the heavier and more adsorption-prone component and may also physically impede flow of the other component. In one series of experiments, separation reversal was observed (the heavier component preferentially separating to the low-pressure side of the membrane). Trends showing increased separation factors at higher temperatures as well as observations of some separation efficiencies in excess of that expected for Knudsen flow suggest that at higher temperatures, molecular screening effects were observed. For most of the experiments, surface effects were stronger and thus apparently overshadow molecular sieving effects.

1. INTRODUCTION

In FY 2000, the Chemical Technology Division at Oak Ridge National Laboratory (ORNL) constructed a test bed for laboratory-scale evaluation of inorganic membranes designed to separate hydrogen from hydrogen/hydrocarbon gas streams. In FY 2001, a 6-month extension of this activity was funded under the Ultra-Clean Fuels Program. Then, in FY 2002, further funding was received from the U.S. Department of Energy's (DOE) National Petroleum Technology Office to continue this work. The inorganic membranes tested were prototypes developed under a different portion of the Fossil Energy Program by the Inorganic Membrane Technology Laboratory (IMTL) located at East Tennessee Technology Park (ETTP) in Oak Ridge, Tennessee. ORNL's experimental role was to test IMTL's membranes using flammable gas mixtures, initially using surrogate binary gas mixtures (e.g. $H_2 + CH_4$ or $H_2 + C_2H_6$), and later (funding permitting) using gas mixtures generated by a laboratory-scale catalytic cracker that had been offered for this purpose by Phillips Petroleum. This report, however, discusses preliminary separation tests on synthetic binary gas mixtures.

The gas membranes tested are in the form of tubes. The test bed is intended to hold one short section of such a tube. Full-scale application will involve many longer parallel tubes. The goal of this work is to determine the capability of specialized inorganic membranes to separate hydrogen from hydrocarbon streams. Realistic gas separation measurements will yield separation factors that incorporate a number of inherent inefficiencies that can be fairly well characterized and predicted from gas transport measurements. To be able to predict performance under conditions other than the specific ones examined experimentally, it is necessary to make the appropriate measurements that allow one to factor out these known, predictable inefficiencies in order to reveal the inherent ideal separation efficiency of the membrane.

Gas separation efficiency will be interpreted by the equation:

$$(\alpha - 1) = E_P \; E_M \; E_C \; E_B \; (\alpha^* - 1) \, . \tag{1}$$

In this equation, α is the measured separation factor, a function of the concentrations of the components in the two product streams:

$$\alpha = [\, Y / (1 - Y) \,] \; / \; [\, X / (1 - X) \,] \; , \tag{2}$$

where Y is the mole fraction of the desired component flowing out the enriched stream and X is the mole fraction of that component flowing out from the depleted stream. In Eq. (1), E_P is a back-pressure correction factor (the ratio of the pressure drop across the membrane to the high-side pressure); E_M is a mixing efficiency, a function of the flow and composition-dependent gas transport parameters, such as the diffusivity and viscosity of the gases; and E_C is a cut correction factor, a function of the fraction of the gas that transits the membrane. These factors will be calculated from measurable experimental parameters following the formulations presented in Ebel [Ref. 1] and Hoglund [Ref. 2]. The specific equations used for these correction factors are summarized in Appendix A.

Two variables in the above equation that have not been mentioned are E_B, the membrane (i.e., barrier) efficiency, and α^*, the ideal separation factor. Separation relying purely on the relative velocity of gas molecules, the so-called "Knudsen flow" (from whence the term "Knudsen membrane" derives), has an α^* equal to the ratio of the average molecular velocities. A design variation on this is the "molecular sieve" membrane, which has pores sufficiently small that it relies on both the molecular velocities plus the effect of different molecular sizes to improve separation of light, small molecules over larger, heavy ones. If the pore size distribution is known, the ideal separation factor for this type of membrane can also be estimated. For these two membrane designs, α^* can be readily calculated, leaving E_B as the ultimate parameter to be determined from the experiment. A third design strategy, the "surface flow" membrane, involves transport via surface adsorption, surface diffusion, and desorption of the more adsorption-prone component. Its ideal separation factor is not as well defined, and the experimental parameters to be determined are the combined factor "E_B (α^* ! 1)." In the data presented below, α^* will be taken as the Knudsen ideal separation factor; all effects unaccounted for by E_C, E_M, etc., will be subsumed into E_B, which will be our figure of merit for the membrane.

The IMTL-designed and manufactured membranes must, due to legacy classification issues, undergo a non-proliferation review prior to commercialization. At this writing, this has been successfully done for over a dozen membrane applications. The process is, however, sufficiently time-consuming that it is not appropriate to carry out during the R&D stage of development and consequently, R&D activities are conducted in a secure laboratory.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 EXPERIMENTAL SYSTEM

The experimental system, largely constructed in FY 2000, was completed, tested, and utilized for separation measurements on an IMTL Knudsen membrane in FY 2001. A simplified schematic of the experimental system is shown in Fig. 1.

The system utilizes premixed binary gas mixtures for the gas inlet supply. The gases are separated in a single pass through the membrane. After measurement (of flow, composition, and pressure), the two streams are safely discarded. Figure 2 shows a photograph of a membrane holder mounted in its temperature-controlled oven. The incoming gas enters the left-hand tube; within the module, the portion of the gas that permeates the membrane departs through the central tube. The portion that does not permeate the membrane departs through the right-hand tube.

The pressure (designated "P" in Fig. 1) in each stream is monitored as is the pressure difference between the two separated streams (ΔP). The pressure sensors are Sensotec FP 2000 series units, with the high-pressure sensor (P_{HI}) having a 0–250-psia range (0–17.2 bar), the low-pressure side (P_{LO}) having a 0–100-psia range (0–6.9 bar), and the differential sensor (ΔP) having a range of ! 15 to +100 psid (! 1 to +6.9 bar). These sensors are located downstream of the membrane module. Calculations of flow resistance and of the pressure drop in this system between the membrane and the pressure gauges yielded values significantly lower than the smallest measurable increment of pressure (0.01 psi or 7 mbar) at the highest accessible flows.

In each stream, the pressures are controlled by back-pressure regulators (designated "BPRs") located downstream of the membrane. These units are TESCOM models 44-4762-24 and 44-2363-24. The high-pressure side has a 0–250-psig (1–18.2-bar) range, and the low-pressure side has a range from vacuum to 0–100 psia (0–6.9 bar). The total flow in the system is controlled upstream of the membrane by a flow controller (designated "FC") and measured downstream in each stream by flowmeters (designated "FM"). These units are Hastings HFM (meter) or HFC (controller) 200-series units. The input unit has a range of 0–2000 sccm (standard cm^3/min) as does the flow sensor on the high-pressure side. The flow sensor on the low-pressure side has a range of 0–1000 sccm. All the flow units are calibrated for N_2. The response of this type of mass flow meter is different for different gases and gas mixtures. Calibration factors for the gases used in this study were obtained from manufacturer literature [Ref. 3].

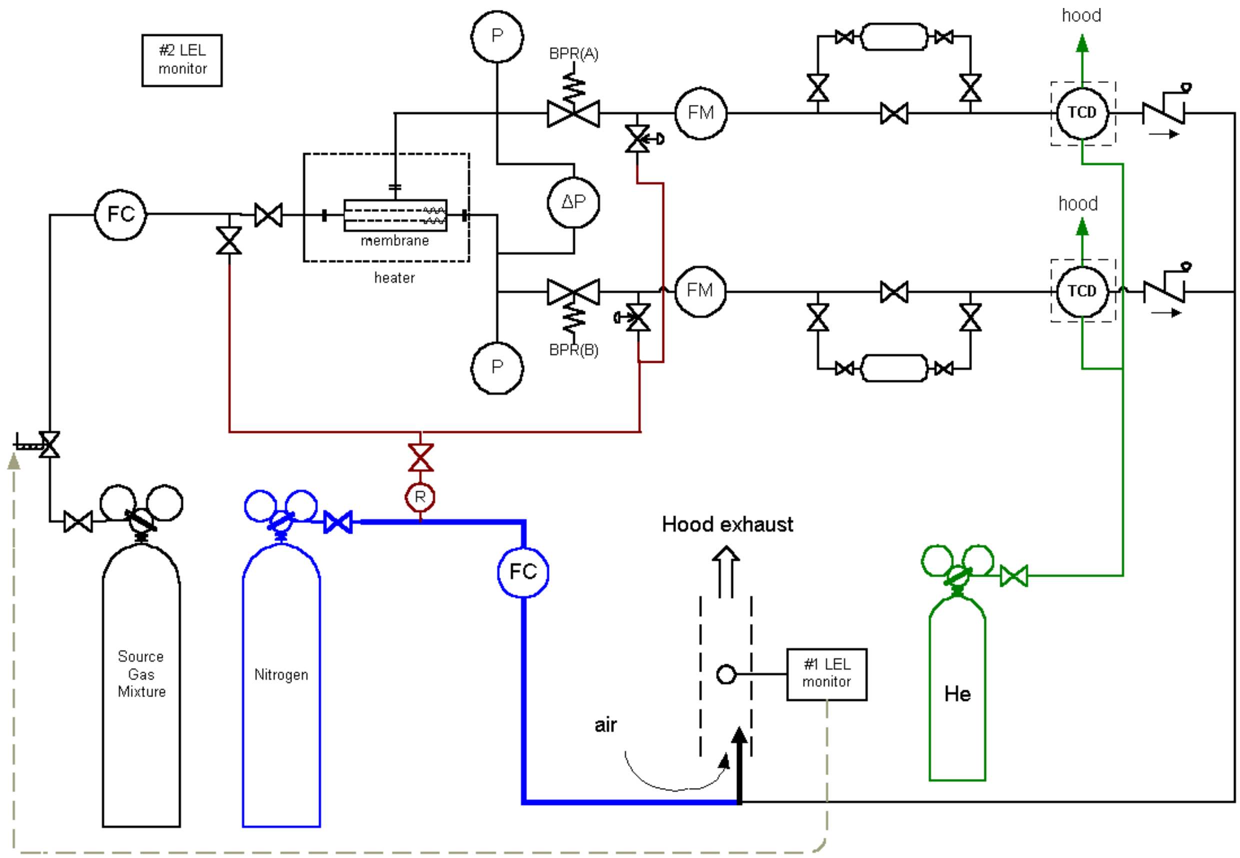

Fig. 1. Schematic of membrane test apparatus, showing major operation elements only.

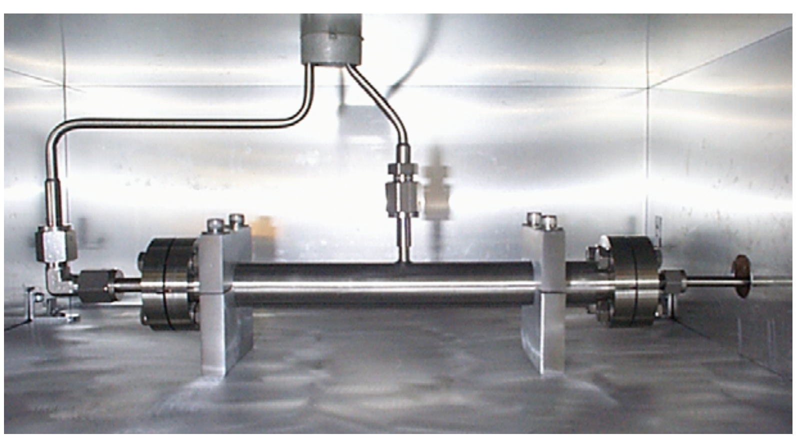

Fig. 2. Membrane holder mounted in oven.

Each stream (or a side-stream thereof) passes through a Gowmac Series 20 thermal conductivity detector (TCD) to determine composition. These units provide a monotonic, though not quite linear, response to varying compositions of gas. The TCD units therefore were calibrated using pure gases or gas mixtures spanning the range of compositions expected in separation experiments. Typically, calibrations were performed using three compositions. For example, for an experiment in which the feed gas was 25% CH_4 and 75% H_2 ,the TCD signals were calibrated with 15, 25, and 50% mixtures of these two gases. Calibrated gas mixtures (both the primary feed gases and small calibration mixtures) were obtained from Air Liquide. From the response of each TCD to the three gas mixtures, a second-order composition-vs-signal curve was derived. Calibrations were usually made at the beginning and end of a series of experiments, and the composition-vs-signal parameters (which actually drifted very little during the course of a series occupying several hours) were interpolated for each measurement based on the time at which the data point was taken. For experiments that required a particularly long time to reach steady state, a single calibration was done immediately after taking the actual experimental data.

Downstream of the TCDs, the two gas streams are mixed and then diluted below the lower flammability limit with a controlled flow of nitrogen. The mix is then exhausted to the laboratory hood ventilation system. Control of the degree of dilution is set by the flow controllers on the source gas stream and the nitrogen diluent stream. To verify that the gas is indeed below the flammability limit, an LEL (lower explosion limit) device continuously monitors the exhaust stream. A second LEL device monitors the general atmosphere in the vicinity of the apparatus. Both LEL devices are MSA Ultima Gas Monitor units with combustible gas detectors.

Flow signals, pressures, temperatures, and TCD signals are measured and recorded by an on-line PC data acquisition system (DAQ; specifically an Instrunet-100 DAQ board using DasyLab version 5.03 software). The collected data acquisition files were post-processed to calculate the composition of the two gas streams. From those compositions, the raw flow readings were corrected to give the actual flows in the two streams.

During the course of an experiment, any of the data streams sent to the DAQ could be plotted in real-time on the PC. Parameters typically displayed were pressures, flows, and compositions. This was especially beneficial in determining when a particular experiment had reached steady state. Due to the finite volume of the tubing and instrumentation, a change in composition at the membrane (induced by a change in the flow, temperature, or pressures) will affect the various sensors at different times. Some time will pass before a new composition at the membrane will appear at the flowmeter, and additional time will elapse before the composition appears at the TCD. Only after the new composition has, in effect, flushed the downstream lines and instruments should the experimental data (temperature, pressure, flows, and compositions) be accepted for purposes of calculating separation performance. In computing this flushing time, one must also consider diffusion from dead-end segments of the piping and instrumentation (which are by design as short as possible). Monitoring real-time plots of flow and composition made it relatively easy to determine when it was appropriate to accept data for a given condition. This process was backed up by a utility program that used system volumes, flows, and pressures to predict the time to a steady-state condition.

2.2 EXPERIMENTAL METHOD

A typical experiment consists of the following steps:

1. The TCDs are calibrated.

2. The membrane holder is brought to the desired temperature.

3. A flow of diluent N_2 is established that will keep the system effluent below the LEL for the mixture at the maximum feed flow contemplated.

4. An open path is set up from the feed through the membrane and through the two TCDs.

5. Target conditions are selected (feed mixture flow, low-side and high-side pressures); the appropriate control elements (feed flowcontroller and the two BPRs) are set to achieve these conditions.

6. TCD outputs are tracked on the DAQ system computer. When the concentrations in both the high- and low-pressure sides of the membrane have stabilized, the outcome of the experiment is recorded—the time of steady state is noted and, as a backup to PC data loss, the key experimental parameters are recorded manually as well.

7. At this point, new target conditions can be selected and the process iterates through (5) and (6).

8. When all desired runs are complete, a second set of TCD calibrations is done.

2.3 MEMBRANES TESTED

Three separate inorganic membranes from IMTL have been tested during the course of this work. All are single tubes. The first tube (designated 1226678-1-1) was a relatively large pore membrane (average pore diameter of 4.5 nm). This tube can be termed a Knudsen membrane since, at that pore size, the separative flow should be dominated by Knudsen flow (also termed "effusive" or "molecular" flow). During 2002, two additional membranes were made available for testing. These had a similar structure but were treated with TEOS (tetraethylorthosilicate) and TMA (trimethyl aluminum). Average pore diameters were closer to molecular dimensions (0.8 and 0.6 nm). These characteristics are summarized in Table 1.

Table 1. Characteristics of membranes tested

Membrane ID	Support layer	Separative layer	Additional treatment	Average pore diam (nm)	Permeance[a]
1226678-1-1	Ni	Al_2O_3	---	4.5	0.4
1230530-89	Ni	Al_2O_3	TEOS/TMA	0.8	0.01
1230530-108	Ni	Al_2O_3	TEOS/TMA	0.6	0.00012

[a]Room-temperature N_2 permeance in units of sccm/(cm Hg-cm^2) at an average pressure of 2 bar [Ref. 4]

Further information on these membranes can be found in Bischoff [Ref. 5].

On each end, the membranes used had a metal ferrule, which was sealed by a Swagelok compression fitting using a carbon fiber composite ferrule. The membrane module was assembled in a dry box at IMTL and provided (capped and filled with inert dry gas) fully assembled. Mounting in the separation system was done with minimal "open" time and with an inert gas flow issuing from the tubing being connected. After installation, an inert purge (N_2 or He) was passed through the membrane for a period ranging from several hours to overnight. These measures were intended to minimize exposure to moisture from the atmosphere.

2.4 GASES USED IN TESTS

Pure gases and mixtures were purchased from Air Liquide. Mixtures were certified to 0.02% absolute composition on a molar basis. The feed gases used were nominally 25 mol % heavy component, 75% light component. Actual compositions of the heavy components of the several mixtures, per Air Liquide's analyses were as follows: Ar in Ar/He: 25.00%; CO_2 in He/CO_2: 25.00%; CH_4 in H_2/CH_4: 25.00%; C_2H_6 in H_2/C_2H_6: 25.02%; and C_3H_8 in H_2/C_3H_8: 24.97%. Pure gases used for TCD reference streams (H_2 or He) were 99.9997% pure.

3. RESULTS

In general, the same sorts of tests were conducted on all three membranes. After preliminary single-gas permeability tests confirmed that the membrane and its seals were intact after transport from IMTL and installation into the separation apparatus, separation tests were conducted using five gas mixtures (H_2/CH_4 , H_2/C_2H_6, H_2/C_3H_8, He/CO_2, and He/Ar). In all cases the gases consisted of approximately 75 mol % of the light component (He or H_2) and 25 mol % of the heavy component.

Experiments spanned the pressure and flow ranges accessible to the instrumentation. Because of the significant permeance differences in the three membranes (see Table 1), some differences existed between the membranes in the parameter space that could be explored. For the Knudsen membrane (1226678-1-1), flow sensor range limitations restricted some experiments (i.e., flows limited to a lower ΔP than the pressure instruments would nominally allow), while for the smaller-pore membranes, the maximum readable ΔP restricted the flow range of experiments. For the smallest-pore-diameter membrane (1230530-108), the *minimum* reliable flowmeter readings prevented measurements at low ΔP and at low exhaust flow.

For each gas, experiments were run at three or four temperatures between room temperature and about 200ºC. A given series of experiments would yield as many as several dozen separation points at average pressures ($\langle P \rangle$, defined as the average of the high- and low-side membrane pressures), ranging from just over 1 bar to about 9 bar (absolute). The cut (the fraction of gas transiting the membrane) ranged from a low of ~10% to a high of ~90%, though high cuts were not possible for the smallest-diameter membranes due to flowmeter range limitations. Many of the limitations on accessible flow and pressure conditions could be relieved by substitution of instrumentation of different ranges.

Accessible temperatures were limited by two factors. One was the heating system (easily modified if necessary), but the other was the membrane sealing system. The membrane must be sealed so that leakage from the high- to the low-pressure side is insignificant compared with the permeating gas flow. However, the system as a whole must also withstand thermal expansion differences as the temperature changes. The sealing system used on these membranes (essentially a compression fitting using a carbon fiber ferrule) handled these conditions satisfactorily to somewhat above 150ºC but, in the 200ºC range, proved to have a limited life before leaking. For the first membrane, the seal functioned in the 200ºC range but leaked on later cooldown. For the other two membranes, the seal began leaking within a day of two of reaching the 200 to 220ºC range. This, combined with the fact that experiments using the smaller-pore membranes took a considerable time to reach steady state (many hours in the case of membrane 1230530-108), caused the number of high-temperature measurements to be limited. The R&D that produced these sample membranes concentrated on development of membranes with favorable characteristics, and not on sealing, which is considered a tractable problem. Different sealing methods must be used to reach higher temperatures.

As previously discussed, experimental data were used to compute separation factors, which were then corrected for the known effects previously alluded to (cut, back pressure, and mixing). A membrane efficiency was then calculated. In effect, this membrane efficiency (E_B) represents the efficiency of the membrane relative to that expected for an ideal Knudsen flow membrane. The factor E_B collects all behavior not readily explained by known gas dynamic and mass balance effects.

Listings of all relevant experimental conditions for each separation data point are included in a series of tables in Appendix B. Appendix B also contains plots of the calculated membrane efficiency E_B vs average pressure. These results are summarized in Table 2, which shows typical observed values of the membrane efficiency for the various gas mixtures and temperatures.

The general trends in separation efficiencies common to all three membranes are as follows:

1. At lower average pressure, the efficiency is typically higher than at higher average pressure. At higher pressures, one would expect a greater fraction of the flow to be in the nonseparative viscous flow regime. Surface flow effects should also typically be greater at higher pressures.

2. Higher temperatures tend to lead to higher separation efficiencies. This effect is markedly different for the three membranes studied. In the Knudsen membrane, the effect was evident but not large.

3. Mixtures containing more condensable gases (e.g., CO_2 and C_3H_8) tend to have lower separation efficiencies and exhibit more of a temperature effect. This is what one would expect of a surface adsorption/flow effect.

Table 2 summarizes the separation efficiencies for the systems and temperatures examined at lower and higher average pressures and for several temperatures. Differences between the membranes can readily be seen. The Knudsen membrane (1226678-1-1) shows a moderate effect that we may attribute to surface-enhanced flow (i.e., lower separation factors, especially for the more condensable gases at lower temperatures). The effect, however, is much more evident in the data for the smaller-pore-diameter membranes. At room temperature and at the higher pressures, membrane 1230530-89 actually showed a reversal of the separation for the propane/hydrogen mixture—that is, the heavier propane preferentially separated through the membrane to the low-pressure side, contrary to normal Knudsen flow expectations. This effect diminished strongly with increasing temperature. The effect was also evident in other pressure regimes and with other gas mixtures, though to a lesser degree for the less condensable gases. A similar effect is seen for membrane 1230530-108. Due to the lower permeance of this membrane, the accessible experimental conditions did not allow measurements at the same high-pressure, low-temperature conditions at which separation reversal was observed in membrane 1230530-89.

Very small pore diameter membranes can in principle enhance separation by molecular sieving or screening. As the experimental data are presented here, this should lead to membrane efficiencies (E_B) greater than 100%. A modest (but reproducible) enhancement above the ideal Knudsen separation factor was seen for He–Ar separations at higher temperatures for the two smaller-pore membranes. Membrane efficiencies >100% were not seen for any of the H_2/HC mixtures, but they were trending rapidly toward high efficiencies at the highest temperatures examined (see, for example, Figs. B.6, B.7, B.11 and B.12).

Absolute separation varies strongly with cut, but this phenomenon is accounted for by a cut correction factor (E_c). After making that correction, separation in the Knudsen membrane (1226678-1-1) showed no further correlation with cut. Membrane 1230530-89, however, showed a significant further cut-related effect: separation efficiencies at low cut were systematically lower than those at high cuts. This effect was stronger at lower average pressures. The range of separation efficiencies for this membrane shown in Table 2 and in Figs. B.6 through B.10 is not scatter: the lower efficiency values are for lower cuts (typically 10 to 25%), while the higher value is for high cuts (typically 75 to 90%). Due to membrane permeance and apparatus limitations, high-cut experiments were not practical on membrane 1230530-108. Therefore, it is not known if this effect occurs in that membrane as well.

Table 2. Experimental average membrane separation efficiency, E_B, expressed in percent[a]

	1226678-1-1			1230530-89			1230530-108		
		Low <P> ~1.5 bar	High<P> ~7 bar		Low <P> ~1.5 bar	High<P> ~8 bar		Low <P> ~4 bar	High<P> ~8 bar
	T (ºC)	E_B	E_B	T (ºC)	E_B	E_B	T (ºC)	E_B	E_B
H_2/CH_4	23	78	63	19	50-58	43	22	30	28
	93	85	70	89	63-71	56	92	40	35
	130	85	70	150	72-82	65	150	51	48
	183	85	70	---	---	---	210	88	---
H_2/C_2H_6	24	75	55	23	24	13	22	22	17
	88	75	57	88	41-46	35	90	28	23
	133	75	60	140	51-57	43	150	37	---
	196	75	55	---	---	---	210	63	---
H_2/C_3H_8	24	52	40	23	31	-15	22	12	---
	90	60	50	88	29	18	90	21	---
	133	63	52	140	39-46	34	150	33	---
	190	65	52	210	45	---	202	53	---
He/CO_2	24	80	57	22	17	8	22	30	26
	93	85	67	88	39-46	34	90	46	42
	130	---	---	145	53-64	48	150	64	62
	196	83	70	---	---	---	210	93	---
He/Ar	23	85	70	23	64-75	55	22	39	35
	93	85	70	84	80-96	75	90	57	55
	130	---	---	150	85-103	75	150	85	81
	196	85	70	---	---	---	220	110-130	---

[a] The value <P> is the average of the high- and low-side pressures of the membrane.

4. DISCUSSION

The results presented in this report utilize a data analysis formulation that attempts to correct for known gas dynamic and mass balance effects to elucidate underlying patterns of membrane behavior. Ultimately, this should make prediction of performance of these membranes more reliable, at least in the general realm of the experimental parameter space explored. It is recognized that the various correction factors used may not accurately represent all pertinent effects, but they do tend to collapse the experimental data to regular and recognizable patterns.

One obvious observation from these experiments is that separation efficiencies observed were on the order of that expected for Knudsen separation or even lower (i.e., E_B <100% for most experiments). Although this performance could, of course, be expected for the Knudsen membrane, it was hoped that separation factors effectively exceeding Knudsen separation would be apparent for the small-pore-diameter membranes as a result of molecular screening effects. Estimated average pore diameters (Table 1) are only slightly larger than approximate molecular diameters (see Table 3 for approximate molecular diameters from viscosity data). In fact, values of E_B >100% were seen for He/Ar mixtures at the highest temperatures examined but not at lower temperatures, and no membrane efficiencies above 100% were observed for any of the hydrogen/hydrocarbon mixtures.

The most likely explanation for this behavior is adsorption and related surface effects. While no data were available to the author regarding adsorption on these specific membranes, some limited data were found relating to adsorption energies for several of the gases of interest on porous glass, a surface somewhat similar [Ref. 6]. Experimental desorption energies are listed in Table 3, and, assuming Langmuir adsorption behavior, estimated surface coverage is listed for two temperatures, 25 and 150ºC. In the coverage calculation, the light component is assumed to be present at 3 bar and the heavy component at 1 bar (i.e., following our feed gas 3:1 mole ratio). For a Knudsen membrane, high coverage of the heavy component would cause only a minor impediment to gas-phase transport of the light component (a reduction in the effective pore size). For the smaller membranes, however, high coverage—that is, high occupancy in the pore structure—could tend to physically impede transport of the light component. The degree of coverage says nothing directly about surface diffusion, but a moderate level of coverage would tend to enhance transport of the adsorbing species as well as inhibit transport of a relatively nonadsorbing species. This report does not address the theory of membrane transport in any detail. These coverage calculations are intended merely to illustrate the plausibility of such effects at the experimental conditions examined in this work.

The strong temperature effects seen in the small-pore membranes and the weaker effects seen in the Knudsen membrane are consistent with a significant surface adsorption and surface diffusion component in the observed separation. These effects are sufficiently strong that the mixture with the most condensable component (H_2/C_3H_8) showed preferential separation of the heavy component to the low-pressure side of the membrane at room temperature. Given the strong apparent surface effects, the simplest explanation for failure to observe dramatic molecular screening effects is that the latter are overshadowed by the former at the conditions examined. At higher temperatures and lower pressures, surface effects will diminish and screening effects should become more evident. Indeed for the gas mixture least prone to adsorption (He/Ar), membrane efficiencies greater than Knudsen separation were observed at the highest temperatures.

These observations have implications for future work. Given the trends in temperature (see, for example, Figs. B.6 through B.15), we would expect membrane efficiencies to improve with increasing temperature as surface effects dwindle. Since plausible operating temperatures in refinery applications are somewhat higher than the maximum we could achieve, it is likely that actual membrane efficiency would be higher than the values observed in this study.

Some additional practical implications of this work are as follows:

1. Performing surface adsorption measurements using the process gases of interest is advisable to assist in estimating the temperature regime in which to expect surface effects.

2. Multiple gas separation experiments are an important supplement to separation estimates derived from single-gas permeabilities, especially for small-pore membranes.

3. Higher-temperature experiments are required to determine the realistic separation behavior, and for this, an improved sealing system needs to be implemented.

Table 3. Parameters relevant to molecular screening and surface effects

	Mol wt (g/mol)	Mol diam[a] (nm) [Ref. 7]	T_C (ºC) [Ref. 8]	B.P. (ºC) [Ref 8]	E_{DES}[b] (kJ/mol) [Ref. 6]	Surf. Coverage (%)[c] at 25ºC	at 150ºC
H_2	2	0.283	-239.9	-252.8	8.2	9	3
He	4	0.255	-267.9	-268.9	2.8	1	0.7
Ar	40	0.354	-122.3	-185.7	10.9	3	0.7
CH_4	16	0.376	-82.1	-164.0	12.5	9	2
C_2H_6	30	0.444	32.2	-88.6	22.2	78	17
C_3H_8	44	0.512	96.8	-42.1			
CO_2	44	0.394	31	-78.5			

[a] Values listed here are the σ parameter of the Lennard-Jones intermolecular potential function.

[b] Desorption energy for the indicated species on porous glass (i.e., silica)

[c] Estimated surface coverage assuming Langmuir isotherm behavior for indicated adsorption energy and pressure of 3 bar for light component and 1 bar for heavy component.

Bischoff [Ref. 5] recently reported results of a series of single-gas permeances (He, O_2, CO_2, and SF_6) for one of the membranes discussed in this report (1230530-89). From those tests, permeance ratios were used to estimate the low-pressure separation factor (α, extrapolated to average P = 0). Bischoff's estimated value of α for He/CO_2 at 23ºC was 1.20, and at 250ºC, it ranged from 1.98 to 3.15. When analyzed as has been done in this work, the E_B at 23ºC would be 9% of Knudsen separation and would range from 42 to 93% at 250ºC. These results are generally in line with the binary gas separation results reported here for that membrane, though the room-temperature value is lower than was obtained in the present work. Permeability values for the other two membranes used in this study were not reported. Data were presented for several additional membranes that showed considerably higher potential selectivity than the membranes tested here [Ref. 5]. Those membranes were produced after this work was completed and unfortunately were not available for separation testing.

5. CONCLUSIONS

Separation efficiency for hydrogen/light hydrocarbon mixtures has been examined for three IMTL-manufactured inorganic membranes. One was a (relatively) large pore-diameter Knudsen membrane and the other two had much smaller pore sizes. In the smaller-pore membranes, separation efficiency was typically lower than Knudsen separation but strongly dependent on temperature, pressure, and gas mixture, with the most condensable gases showing the strongest effect. This finding suggests that the separation is strongly affected by surface effects (i.e., adsorption, diffusion), which enhance the transport of the heavier and more absorption-prone component and possibly also physically occlude the lighter component. In one series of experiments, separation reversal was observed (the heavier component preferentially separating to the low-pressure side of the membrane). This situation could be enhanced by judicious selection of temperatures and pressures, but the optimum conditions would be specific to the particular compounds and concentrations. Therefore, a multi-component separation would be complex.

Molecular sieving effects should enhance the permeation of smaller molecules relative to larger molecules. Separation efficiencies in excess of 100% (ideal Knudsen flow) were observed only for Ar–He separations. On a molecular size basis, Ar/He was the least favorable gas mix in which to see this phenomenon. On the other hand, it was the most favorable from the standpoint of surface effects. For all the other gas mixtures, however, factors we attribute to surface effects were stronger and thus apparently overshadow molecular sieving effects. Surface effects diminish with increasing temperature, but temperatures at which molecular sieving could be seen for the examined hydrogen/hydrocarbon mixtures were not attained.

One overall implication of these experiments is that higher temperatures need to be explored. This would allow further elucidation of surface effects (e.g., help to determine at what temperature they become insignificant for a given gas and membrane), demonstrate the degree to which molecular sieving enhances separation, and also explore the upper limits of operation from the perspective of hydrocarbon thermal decomposition. Follow-on work in this area, should it be done, would require addressing the question of improved high-temperature seals and related questions of membrane and holder differential thermal expansion.

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APPENDIX A, Data Analysis

Methods

This appendix describes the method used for the interpretation of data from these hydrogen–hydrocarbon membrane separation experiments. Analysis of data in this study follows methodology presented by Ebel [Ref. A.1] and Hoglund [Ref. A.2]. These methods were developed for isotope separation processes (i.e., processes in which chemical differences between species do not exist and in which separation factors are relatively small). Many factors that influence separation of *different* chemical species cancel in an isotope separation process: individual adsorption characteristics, surface migration and cooperative effects, and molecular size, to mention a few.

The experimental separation factor, α, for a binary mixture is defined as

$$\alpha = \{ Y / (1 - Y) \} / \{ X / (1 - X) \} , \tag{A.1}$$

where Y is the mole fraction of the desired component in the enriched stream and X is the mole fraction of that component in the depleted stream. The separation factor can be related to the *ideal* stage separation factor in diffusion membranes by

$$(\alpha - 1) = E_B \, E_P \, E_M \, E_C \, (\alpha^* - 1) , \tag{A.2}$$

where

α is the measured separation factor,

α^* is the ideal separation factor,

E_B is the barrier efficiency,

E_P is the back-pressure correction,

E_M is the mixing efficiency,

E_C is the cut correction factor.

The variables E_P, E_M, and E_C correct for parameters related to gas dynamics and mass balance, and are readily calculated. Formulae for these correction factors are discussed below. The barrier efficiency, E_B, can be determined only if we know the ideal separation factor. For a Knudsen membrane, the ideal separation factor is the simply the ratio of the molecular velocities, proportional to the ratio of the square root of the molecular weights of the two species. Molecular sieve effects can be estimated from geometric considerations of the relative size of the two molecules and pore diameters and this can be modified for the effect of molecular diameters for a molecular sieve design. For a surface flow membrane, we will not know a priori the ideal separation factor. In practice, all factors that cannot be accounted for by E_P, E_M, and E_C will be subsumed into the factor E_B.

Correction Factors

The *back-pressure correction factor,* E_P, corrects for the fact that mass flow can pass both from the high-pressure side to the low-pressure side *and* from the low-pressure side to the high. The formula for the back-pressure correction is

$$E_P = 1 - P_{LO}/P_{HI} = \Delta P / P_{HI} \, . \tag{A.3}$$

This is most easily understood for Knudsen flow, since (by definition) gas molecules move independently and thus can as readily move through the membrane in either direction. When there is a finite low-side pressure, the effective separation is of necessity degraded, since some of the (enriched) gas on the low-pressure side will return to the high side.

The *cut correction factor*, E_C, corrects for the fact that gas, as it travels down the tube, is stripped more and more of the preferentially separated component. This effect is related to the *cut*, Θ, which is fraction of the (molar) feed that permeates the membrane. The formula is

$$E_C = 1/\Theta \cdot \ln\left[1/(1 - \Theta)\right] \, . \tag{A.4}$$

As written, this correction factor has a value greater than one. It can account for raw separation factors greater than ideal separation factors.

The *mixing efficiency*, E_M, is an effect that relates to depletion species that preferentially permeates the wall of the membrane. It is a gas transport phenomenon and can be calculated for this membrane separation. The calculation used here [Refs. A.1 and A.2], depends on the assumption of fully developed viscous flow in a tube and would not be valid if other factors intervene. As formulated here, it relates to the diffusional mixing in the high-pressure side of the membrane but does not take into account similar effects in the low-pressure side of the membrane. Since separation along the membrane tube potentially can be fairly high, there is a possibility that effects other than pure laminar flow will apply (e.g., density-driven convection). For our purposes, we will use the mixing efficiency correction as presented in by Ebel [Ref. A.1], recognizing that it is an approximation. Ebel gives the following formula for mixing efficiency:

$$E_M = \exp - \left[(2/f) \; (\mu / D \rho) \; (v / V) \right] , \tag{A.5}$$

where

- f = Fanning friction factor,
- μ = viscosity,
- D = diffusivity,
- ρ = mass density,
- v = average velocity of gas toward tube wall,
- V = average gas velocity along the tube.

The value "μ / D-ρ" is also known as the Schmidt number for the gas. The Fanning friction factor, f, is related to the Reynolds number, N_{rey}. For gases, when $N_{rey} < 2100$, as applied in essentially all experiments here [Ref. A.3],

$$f = 16 / N_{rey} \ . \tag{A.6}$$

Values for D and μ can be calculated for the gases of interest from molecular dynamics theory. The methods and formulae used are standard and repeated in many references. The details are too lengthy to repeat here, but we follow the method presented in Hirschfelder, Curtis, and Bird [Ref. A.4: p.528 for viscosity of single-component gases and binary mixtures; p.539 for binary diffusivity].

Data Analysis

Raw data obtained from a separation experiment consisted of the temperature; the feed flow reading; and, for both the high-pressure and low-pressure gas streams, a flowmeter reading and a thermal conductivity detector (TCD) reading.

TCD readings for gas samples of known composition were recorded before and after a series of separation experiments. Typically three compositions were used for this purpose: one being the feed gas mixture and the other two spanning a wider range of compositions than the expected experimental gas streams after separation. A second-order polynomial fit of TCD reading vs composition was derived from each set of three calibration data points. The polynomial fit parameters derived from calibration readings before and after the actual separation experiments may vary slightly. The fit parameters were assumed to change linearly in time from "before" to "after," and a specific calibration function was interpolated to the recorded time of each separation experiment reading. This calibration function was used to calculate the composition of the gas mixture. This process was performed for each gas stream (i.e., deriving from the high-pressure or low-pressure side of the membrane) and each recorded separation experiment.

Once the compositions of the two streams for a given experiment were known, the experimental separation factor, α, was calculated per Eq. (A.1).

The thermal mass flowmeters exhibit differing sensitivities to different gases. For pure gases, the manufacturer has tabulated correction factors that enable one to correct the readings of an instrument calibrated for (as in this case) N_2 for another gas (e.g., He). Single-gas correction factors are listed in Table A-1.

Table A.1. Gas correction factors (C) for Hastings HFM/C-200 series units [Ref. A.5]

Gas	C
H_2	1.009
He	1.382
N_2	1.000
CO_2	0.743
CH_4	0.770
C_2H_6	0.482
C_3H_8	0.357
Ar	1.382

The correction factor for a binary gas mixture is given by

$$C_{1,2} = \left(X_1 / C_1 + X_2 / C_2 \right)^{-1} , \tag{A.7}$$

where $C_{1,2}$ is the correction factor for the mixture consisting of mole fraction X_1 of gas 1 and mole fraction X_2 of gas 2, and C_1 and C_2 are the corresponding single-gas correction factors. Applying these correction factors to the (known) feed composition and the measured high- and low-pressure stream compositions, the true flows are calculated from the indicated readings.

Pressure readings are taken from the low-pressure transducer and the ΔP transducer. The temperature readings are taken directly form the instrumentation.

With these data, it is now possible to calculate the various correction factors: E_P, E_M, and E_C , as described above. For purposes of this work, the ideal separation factor, α^*, is simply taken as the ideal Knudsen separation factor, namely

$$\alpha^* = \left(M_2 / M_1 \right)^{1/2} , \qquad \text{(A.8)}$$

While it would be possible to estimate screening effects, that is, differences in transmission probability due to differing sizes of molecules, membrane-to-membrane comparisons are more readily made using the simpler Knudsen factor for all three membranes.

From the correction factors, experimental separation factor, and ideal separation factor, the membrane efficiency, E_B, is calculated using Eq. (A.2). In effect, E_B contains all non-Knudsen effects, be they surface flow, molecular screening, physical leaks, viscous flow, or inadequacy of approximations made in the correction factor formulations. Still, it is useful to utilize the various correction factors, since the raw separation factors vary widely, whereas E_B shows trends and patterns much more conducive to direct interpretation of data or, more importantly, prediction of membrane behavior under different conditions.

References for Appendix A

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APPENDIX B, Experimental Data

Tables B.1 through B.15 contain experimental data and the results derived from that data, which are also plotted in Figs. B.1 through B.15. Pressures and temperatures are taken from the data acquisition (DAQ) record of the instrument readings (unit-converted to bars in the case of pressure). Flows are converted from the flowmeter readings per the composition-related scaling discussed in Appendix A. Concentrations are interpreted from the thermal conductivity detector (TCD) readings of the separated streams and of calibration gases. The observed separation factor and the several correction factors are then calculated from these experimental data per the methods in Appendix A. The final result is the membrane efficiency, E_B, expressing the separation performance relative to that expected for perfect Knudsen separation (for which $E_B = 1$).

Table B.1. Separation results for IMTL membrane 1226678-1-1: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.5	6.842	1.085	850.0	255.8	0.24%	0.28%	1.226	0.137	1.904	0.825	0.575
23.5	4.254	1.060	805.1	299.0	0.23%	0.29%	1.323	0.199	1.792	0.833	0.593
23.5	3.063	0.410	308.6	803.2	0.23%	0.25%	1.137	0.118	1.171	0.932	0.583
23.4	2.736	0.736	554.0	556.5	0.22%	0.27%	1.295	0.212	1.385	0.882	0.623
23.4	2.327	1.124	830.3	272.7	0.23%	0.31%	1.577	0.326	1.856	0.828	0.630
23.4	1.822	0.367	271.4	839.9	0.22%	0.25%	1.209	0.168	1.147	0.940	0.633
23.5	1.477	0.702	521.8	589.4	0.21%	0.28%	1.474	0.322	1.350	0.888	0.670
23.5	1.108	1.052	770.4	335.2	0.21%	0.33%	1.883	0.487	1.713	0.840	0.689
23.5	1.034	1.110	808.8	295.3	0.21%	0.35%	1.987	0.518	1.800	0.832	0.696
23.5	1.017	0.713	519.8	212.7	0.21%	0.33%	1.810	0.412	1.743	0.889	0.694
23.5	1.000	0.348	254.1	478.2	0.21%	0.27%	1.374	0.258	1.228	0.944	0.684
23.5	1.000	0.325	235.4	219.9	0.22%	0.28%	1.394	0.245	1.408	0.948	0.658
23.5	0.999	0.310	221.0	88.4	0.23%	0.30%	1.438	0.237	1.754	0.951	0.607
23.6	2.059	0.320	234.2	220.6	0.23%	0.26%	1.197	0.135	1.405	0.948	0.601
23.6	2.056	0.336	248.1	489.2	0.23%	0.26%	1.186	0.141	1.219	0.945	0.629
23.6	2.032	0.711	524.5	212.2	0.23%	0.30%	1.476	0.259	1.748	0.888	0.647
23.6	2.032	0.694	508.8	129.4	0.23%	0.31%	1.531	0.255	2.002	0.891	0.640
23.7	4.274	0.683	519.1	216.6	0.24%	0.28%	1.238	0.138	1.733	0.889	0.613
23.7	6.773	0.718	564.7	166.9	0.24%	0.27%	1.175	0.096	1.915	0.880	0.593
23.5	1.022	1.203	901.9	885.7	0.19%	0.30%	1.781	0.541	1.392	0.815	0.696
23.6	1.018	1.143	819.9	145.4	0.22%	0.40%	2.309	0.529	2.229	0.830	0.731
23.5	1.017	1.124	799.0	82.3	0.23%	0.43%	2.529	0.525	2.615	0.834	0.730
24.3	1.047	1.142	744.8	219.6	0.21%	0.37%	2.203	0.522	1.916	0.845	0.779
24.3	1.050	1.170	788.9	1088.2	0.19%	0.29%	1.779	0.527	1.297	0.837	0.745
24.3	1.679	0.571	386.6	1495.2	0.21%	0.26%	1.363	0.254	1.119	0.916	0.764
24.4	4.313	0.984	682.5	429.9	0.23%	0.28%	1.302	0.186	1.550	0.857	0.669
96.0	0.999	0.369	225.2	229.2	0.21%	0.29%	1.502	0.270	1.381	0.957	0.770
95.2	0.999	0.411	254.1	477.6	20.16%	27.43%	1.497	0.291	1.228	0.952	0.799
94.1	1.000	0.425	265.8	848.6	19.62%	26.57%	1.482	0.298	1.142	0.949	0.815
92.9	1.000	0.423	293.5	1567.6	19.06%	26.02%	1.493	0.297	1.088	0.944	0.883

Table B.1. Separation results for IMTL membrane 1226678-1-1: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
90.1	1.346	0.647	404.2	237.8	21.27%	31.00%	1.663	0.325	1.577	0.923	0.767
91.0	1.349	0.690	433.0	302.3	20.89%	30.59%	1.669	0.338	1.509	0.918	0.780
92.0	1.347	0.651	413.2	694.3	19.96%	27.83%	1.547	0.326	1.252	0.922	0.795
93.0	1.349	0.721	463.8	1399.0	19.20%	26.81%	1.542	0.348	1.150	0.913	0.810
95.2	1.372	1.498	917.1	177.3	21.93%	40.41%	2.414	0.522	2.172	0.836	0.816
95.6	1.399	1.426	927.7	912.8	19.33%	30.66%	1.845	0.505	1.391	0.834	0.789
93.5	3.157	0.750	475.8	259.0	22.82%	28.81%	1.369	0.192	1.610	0.911	0.716
92.1	3.157	0.737	471.9	637.6	22.11%	26.99%	1.303	0.189	1.302	0.911	0.737
90.8	3.153	0.738	476.9	1383.1	21.64%	26.04%	1.275	0.190	1.155	0.910	0.753
89.8	3.177	1.394	883.4	219.8	22.84%	33.22%	1.680	0.305	2.015	0.840	0.721
90.3	3.158	1.405	907.5	950.4	21.27%	28.43%	1.470	0.308	1.372	0.836	0.728
94.1	5.142	0.730	476.3	253.5	23.55%	27.55%	1.235	0.124	1.620	0.911	0.699
95.6	5.140	0.779	509.9	603.5	23.01%	26.58%	1.211	0.132	1.337	0.905	0.725
96.2	5.131	0.830	544.9	1317.7	22.58%	25.93%	1.200	0.139	1.183	0.899	0.739
96.0	4.528	1.383	896.4	956.1	22.04%	27.66%	1.353	0.234	1.367	0.840	0.719
94.5	4.540	1.325	850.8	253.9	23.18%	30.77%	1.473	0.226	1.909	0.847	0.708
92.5	6.619	0.719	479.8	633.5	23.42%	26.11%	1.155	0.098	1.308	0.910	0.727
90.4	6.514	0.754	501.5	225.8	23.84%	27.41%	1.206	0.104	1.696	0.906	0.708
90.1	6.537	0.789	531.1	1334.8	23.08%	25.72%	1.154	0.108	1.177	0.901	0.740
90.6	6.587	1.365	923.2	932.0	22.79%	27.09%	1.259	0.172	1.383	0.834	0.714
92.9	6.578	1.312	867.2	230.7	23.70%	29.53%	1.349	0.166	1.975	0.844	0.688
137.6	1.003	0.691	400.5	720.6	18.78%	28.45%	1.720	0.408	1.237	0.930	0.839
137.3	1.001	0.606	345.6	210.7	20.56%	32.19%	1.834	0.377	1.563	0.939	0.825
137.8	2.126	1.492	869.0	240.5	21.96%	36.19%	2.016	0.412	1.952	0.854	0.808
138.4	2.752	0.892	539.6	579.3	21.55%	28.14%	1.425	0.245	1.365	0.907	0.768
139.2	2.765	0.872	509.0	118.1	23.18%	32.45%	1.592	0.240	2.057	0.912	0.720
138.6	4.659	1.527	924.5	226.6	23.21%	32.26%	1.576	0.247	2.024	0.846	0.745
137.4	5.290	0.857	532.6	160.8	23.73%	28.93%	1.309	0.139	1.902	0.908	0.701
138.8	6.596	0.700	443.6	249.2	23.86%	27.03%	1.183	0.096	1.597	0.923	0.706
138.4	6.590	1.385	875.5	277.3	23.55%	29.55%	1.362	0.174	1.876	0.853	0.712

Table B.1. Separation results for IMTL membrane 1226678-1-1: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
179.2	1.019	0.610	418.1	139.3	21.55%	34.79%	1.942	0.374	1.849	0.931	0.799
180.0	1.021	0.625	450.3	669.2	19.22%	28.56%	1.681	0.380	1.279	0.926	0.828
180.9	1.171	1.222	869.0	241.6	20.99%	38.84%	2.391	0.511	1.950	0.863	0.885
182.1	2.422	1.283	923.8	185.5	22.55%	35.83%	1.917	0.346	2.148	0.855	0.789
182.7	3.168	0.596	441.6	677.2	22.21%	26.36%	1.253	0.158	1.272	0.928	0.742
183.4	3.171	0.547	403.2	190.2	23.10%	27.95%	1.292	0.147	1.674	0.934	0.693
184.5	4.601	0.522	391.6	200.8	23.52%	26.88%	1.195	0.102	1.637	0.936	0.683
185.2	4.606	0.527	398.6	726.7	22.93%	25.60%	1.156	0.103	1.235	0.935	0.721
185.7	4.619	1.150	862.6	256.1	23.05%	30.03%	1.433	0.199	1.912	0.865	0.718
186.4	6.646	0.508	395.7	730.1	23.37%	25.29%	1.110	0.071	1.232	0.936	0.733
186.9	6.650	0.485	375.5	218.2	23.74%	25.96%	1.127	0.068	1.583	0.939	0.685
187.3	6.656	1.037	796.4	314.6	23.35%	27.83%	1.266	0.135	1.760	0.875	0.701

Table B.2. Separation results for IMTL membrane 1226678-1-1: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.1	6.871	0.522	331.3	353.0	23.81%	26.17%	1.135	0.071	1.367	0.908	0.535
23.1	6.876	0.535	341.5	755.0	23.48%	25.66%	1.125	0.072	1.198	0.905	0.555
23.1	6.204	1.178	740.7	351.0	23.27%	28.54%	1.318	0.160	1.672	0.805	0.514
23.1	4.246	0.512	313.7	196.1	23.44%	27.50%	1.239	0.108	1.553	0.912	0.546
23.1	4.248	0.481	296.8	480.4	22.92%	26.20%	1.194	0.102	1.260	0.917	0.573
23.1	3.443	1.288	777.1	150.9	23.23%	33.84%	1.691	0.272	2.169	0.797	0.511
23.2	2.861	0.221	131.5	799.9	23.14%	25.26%	1.123	0.072	1.078	0.962	0.575
23.2	1.746	1.269	755.6	172.1	22.00%	38.20%	2.191	0.421	2.068	0.802	0.594
23.2	2.460	0.615	377.4	554.4	21.34%	27.43%	1.393	0.200	1.282	0.895	0.596
23.2	2.451	0.563	337.0	127.8	22.77%	30.83%	1.512	0.187	1.781	0.906	0.591
23.2	1.038	0.541	322.7	141.6	20.83%	34.54%	2.005	0.342	1.709	0.910	0.657
23.3	1.047	0.655	406.2	529.7	18.79%	29.85%	1.839	0.385	1.311	0.888	0.651
23.2	1.331	0.387	234.7	701.4	20.11%	26.63%	1.442	0.225	1.151	0.934	0.636
23.2	1.080	1.234	736.3	196.2	20.89%	40.65%	2.593	0.533	1.974	0.806	0.654
86.4	1.062	0.690	336.3	126.3	20.36%	37.48%	2.345	0.394	1.786	0.918	0.725
86.9	1.064	0.724	345.7	424.9	18.28%	30.58%	1.968	0.405	1.327	0.916	0.685
87.7	1.084	1.130	560.8	210.1	19.52%	39.69%	2.714	0.510	1.787	0.867	0.754
89.0	1.880	1.300	633.7	136.8	21.67%	40.60%	2.470	0.409	2.102	0.852	0.699
89.3	2.246	0.938	467.0	304.3	20.76%	31.63%	1.765	0.294	1.536	0.888	0.663
88.6	2.240	0.906	442.7	136.3	21.89%	35.10%	1.929	0.288	1.892	0.894	0.664
86.6	3.655	0.585	288.9	172.4	22.89%	28.56%	1.347	0.138	1.572	0.929	0.598
87.1	3.605	0.634	298.1	475.0	22.12%	26.79%	1.288	0.149	1.263	0.927	0.573
88.7	3.131	1.096	558.7	215.7	21.93%	32.88%	1.744	0.259	1.772	0.868	0.650
89.2	6.412	1.104	563.8	209.9	23.27%	29.47%	1.378	0.147	1.790	0.867	0.577
88.4	6.078	1.421	728.3	360.2	22.73%	29.61%	1.430	0.190	1.653	0.831	0.574
86.7	5.966	0.362	183.3	200.2	23.95%	26.04%	1.118	0.057	1.360	0.954	0.554
87.9	1.421	0.506	245.4	138.9	21.22%	31.88%	1.737	0.262	1.594	0.940	0.653

Table B.2. Separation results for IMTL membrane 1226678-1-1: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
136.7	1.054	1.414	210.8	254.1	16.57%	31.62%	2.328	0.573	1.332	0.952	0.636
136.1	1.042	1.028	248.6	215.8	17.50%	33.51%	2.376	0.497	1.432	0.944	0.714
137.1	2.462	0.990	254.6	210.4	20.25%	30.43%	1.723	0.287	1.448	0.943	0.643
136.5	2.461	0.989	258.4	206.3	20.28%	30.53%	1.728	0.287	1.460	0.942	0.643
135.4	2.088	1.292	353.4	112.9	20.76%	37.48%	2.289	0.382	1.871	0.921	0.681
136.0	2.114	1.358	400.4	370.1	18.88%	31.39%	1.966	0.391	1.411	0.911	0.669
136.5	2.121	1.348	403.7	366.8	18.89%	31.45%	1.970	0.389	1.417	0.910	0.674
136.7	2.147	2.037	637.9	132.8	21.07%	42.23%	2.738	0.487	2.124	0.862	0.678
136.3	2.147	2.031	648.7	122.5	21.27%	42.93%	2.784	0.486	2.187	0.860	0.679
135.9	2.147	2.026	658.3	113.1	21.47%	43.60%	2.827	0.485	2.250	0.858	0.679
136.1	5.820	1.692	592.7	178.5	22.62%	32.36%	1.637	0.225	1.904	0.871	0.593
136.8	6.719	0.824	297.6	473.1	22.55%	26.30%	1.225	0.109	1.264	0.933	0.609
133.2	6.698	0.448	163.3	605.5	23.19%	25.32%	1.123	0.063	1.124	0.963	0.632
129.2	1.742	0.857	310.1	155.5	20.41%	33.83%	1.993	0.330	1.647	0.930	0.685
129.0	1.744	0.909	343.1	430.0	18.87%	29.77%	1.822	0.343	1.322	0.922	0.685
130.3	1.756	1.570	592.4	181.2	20.28%	40.12%	2.634	0.472	1.895	0.870	0.731
132.9	1.734	0.419	158.6	613.8	20.19%	26.15%	1.400	0.195	1.119	0.964	0.663
134.6	1.114	1.031	410.8	362.2	17.65%	33.27%	2.327	0.481	1.426	0.909	0.741
135.2	1.132	1.530	617.3	155.0	19.88%	45.22%	3.327	0.575	2.009	0.866	0.810
135.0	1.132	1.525	622.2	149.8	19.99%	45.63%	3.360	0.574	2.034	0.865	0.813
134.8	1.132	1.520	628.6	143.5	20.14%	46.14%	3.398	0.573	2.067	0.864	0.816
134.8	1.133	1.526	636.9	135.5	20.33%	46.73%	3.439	0.574	2.111	0.862	0.813
135.7	1.090	0.376	156.0	148.6	20.47%	29.83%	1.652	0.256	1.402	0.964	0.655
135.9	1.091	0.378	159.0	146.1	20.38%	29.96%	1.671	0.257	1.413	0.964	0.667
195.7	1.144	0.449	295.8	173.3	20.87%	32.20%	1.801	0.282	1.579	0.939	0.667
195.8	1.161	0.510	349.3	596.3	18.95%	28.54%	1.709	0.305	1.248	0.929	0.697
195.8	1.235	0.996	672.0	274.3	19.88%	37.83%	2.452	0.447	1.744	0.867	0.749
195.9	2.086	0.981	660.1	286.4	21.12%	34.03%	1.927	0.320	1.714	0.869	0.676
195.9	2.500	0.571	386.5	559.4	21.29%	27.54%	1.406	0.186	1.286	0.921	0.641
195.9	2.509	0.507	335.3	166.5	22.60%	29.74%	1.450	0.168	1.651	0.931	0.606

Table B.2. Separation results for IMTL membrane 1226678-1-1: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
195.9	4.103	0.479	321.1	180.3	23.40%	27.87%	1.265	0.105	1.597	0.934	0.590
196.0	4.107	0.482	326.8	616.8	22.73%	26.21%	1.207	0.105	1.228	0.933	0.600
196.0	4.123	0.955	647.8	297.3	22.60%	30.27%	1.487	0.188	1.687	0.872	0.612
196.1	5.235	0.968	660.9	283.5	23.05%	29.54%	1.400	0.156	1.719	0.869	0.597
196.0	5.239	0.459	315.0	629.2	23.12%	25.91%	1.163	0.081	1.217	0.935	0.619
196.0	5.242	0.432	294.1	175.8	23.76%	26.98%	1.186	0.076	1.571	0.940	0.575
196.2	6.686	0.437	301.1	167.8	24.07%	26.73%	1.151	0.061	1.600	0.938	0.568
196.2	6.694	0.439	304.9	637.1	23.58%	25.70%	1.121	0.061	1.208	0.937	0.604
196.2	6.700	0.939	652.6	293.4	23.44%	28.71%	1.315	0.123	1.697	0.871	0.604

Table B.3. Separation results for IMTL membrane 1226678-1-1: 24.97% C_3H_8 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.9	0.993	0.264	144.5	122.1	21.66%	29.05%	1.481	0.210	1.441	0.879	0.490
23.9	0.994	0.281	157.5	282.3	20.68%	27.46%	1.452	0.221	1.238	0.833	0.539
23.9	1.001	0.536	300.4	141.7	20.84%	33.71%	1.932	0.349	1.675	0.932	0.464
23.9	1.003	0.615	341.3	101.6	21.44%	36.76%	2.130	0.380	1.911	0.882	0.478
23.9	2.082	0.395	219.5	221.4	22.36%	27.70%	1.330	0.159	1.384	0.828	0.489
24.0	1.830	0.600	331.0	111.6	22.52%	32.26%	1.638	0.247	1.843	0.940	0.404
24.0	2.285	0.192	104.8	334.8	23.16%	25.58%	1.141	0.078	1.142	0.888	0.484
24.0	4.155	0.544	300.8	141.3	23.63%	27.89%	1.250	0.116	1.676	0.840	0.415
24.0	4.148	0.554	309.1	505.8	23.01%	26.29%	1.194	0.118	1.257	0.832	0.427
24.0	6.404	0.525	290.8	146.5	24.11%	26.74%	1.149	0.076	1.645	0.889	0.364
24.1	6.405	0.562	315.8	635.2	23.59%	25.71%	1.121	0.081	1.215	0.944	0.353
88.8	0.991	0.292	140.7	126.1	20.91%	29.44%	1.579	0.227	1.421	0.958	0.507
89.1	0.992	0.346	172.3	266.5	19.62%	28.35%	1.621	0.259	1.270	0.949	0.539
90.1	0.996	0.584	291.3	149.8	19.77%	34.60%	2.147	0.369	1.635	0.915	0.562
90.3	0.999	0.691	340.2	101.6	20.56%	38.98%	2.469	0.409	1.909	0.901	0.566
89.4	2.111	0.676	340.1	101.3	22.22%	33.93%	1.798	0.242	1.911	0.901	0.518
89.2	2.494	0.295	144.4	293.4	22.37%	26.17%	1.230	0.106	1.213	0.957	0.508
90.4	4.172	0.575	287.4	152.9	23.09%	28.25%	1.312	0.121	1.621	0.916	0.470
90.2	4.162	0.601	305.5	647.4	22.16%	26.25%	1.250	0.126	1.206	0.911	0.490
89.8	6.602	0.586	300.1	140.3	23.79%	27.35%	1.206	0.081	1.679	0.912	0.447
90.5	6.600	0.584	302.7	631.5	23.15%	25.81%	1.155	0.081	1.209	0.912	0.468
132.1	0.994	0.349	156.7	110.9	20.30%	31.53%	1.807	0.260	1.504	0.957	0.585
132.3	0.995	0.364	169.8	270.6	18.97%	28.75%	1.724	0.268	1.263	0.953	0.608
133.4	1.002	0.644	308.3	134.1	19.44%	37.44%	2.481	0.391	1.713	0.917	0.653
133.9	2.055	0.686	339.1	105.1	21.72%	35.06%	1.946	0.250	1.888	0.909	0.596
132.4	2.436	0.314	151.6	289.5	22.00%	26.42%	1.273	0.114	1.225	0.958	0.551
134.1	6.583	0.616	312.9	130.6	23.64%	27.81%	1.245	0.086	1.733	0.916	0.488
132.3	6.580	0.613	318.9	631.5	22.84%	25.97%	1.185	0.085	1.218	0.914	0.529
125.2	4.114	0.626	320.4	119.1	23.12%	29.67%	1.403	0.132	1.791	0.912	0.505

Table B.3. Separation results for IMTL membrane 1226678-1-1: 24.97% C_3H_8 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
124.6	4.116	0.703	371.4	583.9	21.77%	26.99%	1.328	0.146	1.266	0.899	0.536
189.2	1.031	0.443	269.6	137.9	20.37%	34.01%	2.015	0.300	1.638	0.933	0.599
189.4	1.037	0.467	298.1	520.8	18.22%	28.88%	1.823	0.310	1.243	0.926	0.624
189.5	1.072	0.879	551.9	269.3	18.88%	37.45%	2.572	0.451	1.659	0.867	0.657
189.9	2.815	0.881	551.4	271.2	21.60%	31.93%	1.702	0.238	1.655	0.867	0.556
189.8	3.227	0.508	318.3	501.6	21.83%	26.97%	1.323	0.136	1.266	0.921	0.551
189.9	3.263	0.439	279.4	132.9	22.99%	29.00%	1.368	0.119	1.671	0.930	0.542
190.0	5.294	0.424	264.7	147.3	23.73%	27.30%	1.207	0.074	1.601	0.934	0.506
190.1	5.299	0.416	262.5	559.6	23.19%	25.87%	1.156	0.073	1.205	0.935	0.514
190.1	5.311	0.802	511.3	316.3	22.80%	28.43%	1.345	0.131	1.557	0.877	0.522
190.2	6.508	1.006	640.9	186.5	23.47%	30.07%	1.402	0.134	1.923	0.848	0.499
190.2	6.518	0.488	312.4	509.6	23.28%	26.00%	1.158	0.070	1.258	0.923	0.529
190.1	2.098	0.973	609.7	216.5	21.21%	35.66%	2.059	0.317	1.815	0.855	0.584
190.1	2.085	0.495	312.6	511.7	20.67%	27.64%	1.466	0.192	1.257	0.923	0.568
190.1	2.090	0.420	257.9	153.3	22.08%	29.73%	1.493	0.167	1.573	0.936	0.542

Table B.4. Separation results for IMTL membrane 1226678-1-1: 25% CO_2 in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.8	1.051	0.743	367.6	76.2	21.46%	42.19%	2.671	0.414	2.128	0.901	0.909
23.7	1.030	0.789	408.1	374.4	18.57%	32.52%	2.113	0.434	1.413	0.890	0.880
23.8	1.038	0.878	466.7	1350.8	16.95%	28.36%	1.940	0.458	1.156	0.876	0.875
23.9	4.196	1.932	1009.0	804.0	21.31%	29.93%	1.577	0.315	1.461	0.751	0.721
23.9	3.180	0.605	307.8	361.2	22.01%	27.82%	1.366	0.160	1.340	0.916	0.806
29.3	3.184	0.605	307.0	364.2	21.91%	27.79%	1.371	0.160	1.337	0.917	0.818
25.2	1.010	0.790	392.2	55.8	22.25%	44.09%	2.756	0.439	2.379	0.895	0.812
25.2	2.320	2.162	1111.4	581.1	20.97%	32.79%	1.839	0.482	1.628	0.730	0.632
25.3	6.198	2.117	1120.8	1130.5	22.12%	27.84%	1.358	0.255	1.384	0.728	0.603
25.4	4.194	1.937	1009.1	800.6	21.60%	29.36%	1.509	0.316	1.463	0.751	0.633
24	1.010	0.451	226.3	104.7	21.34%	33.27%	1.838	0.309	1.683	0.938	0.742
24	1.003	0.288	144.3	186.3	21.05%	28.11%	1.466	0.223	1.314	0.960	0.715
24	1.040	0.750	374.7	67.5	22.10%	42.25%	2.580	0.419	2.218	0.899	0.817
24	1.029	0.755	375.8	66.1	22.13%	42.71%	2.623	0.423	2.234	0.899	0.824
24	1.030	0.761	389.2	168.1	20.35%	36.18%	2.219	0.425	1.716	0.895	0.806
24	1.031	0.786	410.6	373.2	18.95%	31.78%	1.992	0.433	1.416	0.890	0.785
24	1.035	0.845	452.4	1245.0	17.42%	27.78%	1.824	0.450	1.163	0.879	0.774
24	1.034	0.843	451.4	1247.0	17.38%	27.77%	1.828	0.449	1.162	0.880	0.778
24	1.036	0.879	473.7	1793.2	17.01%	27.10%	1.814	0.459	1.122	0.874	0.781
24	2.281	2.246	1168.6	1082.7	20.23%	30.30%	1.714	0.496	1.410	0.717	0.614
24	2.278	2.175	1118.7	568.3	21.07%	32.94%	1.840	0.489	1.641	0.728	0.622
24	2.278	2.173	1108.3	386.7	21.64%	34.93%	1.944	0.488	1.824	0.730	0.627
24	2.277	2.138	1063.6	109.0	23.43%	41.19%	2.289	0.484	2.619	0.739	0.593
24	2.275	2.117	1043.7	57.8	24.08%	43.31%	2.408	0.482	3.111	0.743	0.545
24	4.158	1.892	969.5	201.2	23.22%	33.97%	1.701	0.313	2.126	0.759	0.600
24	4.192	1.941	1015.6	800.4	21.67%	29.34%	1.501	0.317	1.465	0.749	0.623
24	4.205	1.959	1031.3	1229.4	21.22%	28.24%	1.461	0.318	1.335	0.746	0.629
24	6.201	2.119	1120.4	1132.2	22.17%	27.85%	1.355	0.255	1.383	0.727	0.599
24	6.214	2.079	1092.3	595.6	22.69%	29.24%	1.409	0.251	1.610	0.733	0.596
24	6.224	2.053	1062.5	173.1	23.84%	32.21%	1.518	0.248	2.286	0.739	0.534

Table B.4. Separation results for IMTL membrane 1226678-1-1: 25% CO_2 in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
85.9	3.176	0.584	260.1	239.7	22.19%	28.12%	1.372	0.155	1.412	0.937	0.782
92.3	3.186	0.572	250.0	124.8	22.81%	29.31%	1.403	0.152	1.649	0.940	0.738
93.7	3.171	0.642	285.6	602.3	21.45%	26.82%	1.341	0.168	1.207	0.932	0.778
90.6	3.188	0.673	302.2	1103.5	21.07%	26.21%	1.330	0.174	1.126	0.928	0.783
89.2	6.171	1.419	663.6	1597.8	21.51%	26.57%	1.321	0.187	1.184	0.848	0.738
90.6	6.167	1.336	621.2	1072.2	21.78%	26.94%	1.324	0.178	1.246	0.857	0.736
92.6	6.171	1.325	610.1	507.7	22.28%	28.23%	1.372	0.177	1.446	0.860	0.731
94.8	6.171	1.303	592.0	239.9	22.94%	29.90%	1.433	0.174	1.747	0.864	0.709
95.7	6.171	1.276	573.8	146.1	23.41%	31.01%	1.471	0.171	2.001	0.868	0.683
92.0	6.148	2.232	1011.1	273.8	22.96%	32.50%	1.615	0.266	1.965	0.778	0.652
90.6	6.163	2.277	1046.6	645.7	22.08%	29.81%	1.499	0.270	1.558	0.771	0.664
89.8	6.174	2.310	1072.9	1180.2	21.53%	28.25%	1.435	0.272	1.358	0.766	0.663
91.7	3.789	2.101	935.0	185.0	22.73%	36.60%	1.962	0.357	2.157	0.793	0.681
93.4	3.789	2.153	981.0	707.2	20.95%	30.80%	1.680	0.362	1.497	0.785	0.689
95.0	3.789	2.176	999.2	1257.6	20.27%	28.89%	1.598	0.365	1.321	0.782	0.685
96.0	3.788	2.106	946.8	393.8	21.66%	33.14%	1.793	0.357	1.735	0.792	0.697
95.7	1.017	1.991	875.1	240.0	20.10%	43.59%	3.072	0.662	1.957	0.806	0.856
93.3	1.016	1.936	840.5	135.8	21.29%	49.01%	3.553	0.656	2.291	0.812	0.903
92.1	1.017	1.966	888.2	460.7	18.72%	37.61%	2.617	0.659	1.632	0.802	0.809
91.1	1.018	2.010	922.3	772.7	17.80%	33.92%	2.372	0.664	1.444	0.795	0.777
90.3	1.018	2.018	941.6	1315.7	16.93%	30.98%	2.202	0.665	1.294	0.791	0.762
196.3	1.070	0.921	468.4	887.3	17.63%	28.93%	1.901	0.462	1.227	0.906	0.756
196.3	1.117	1.617	890.1	465.7	18.86%	36.92%	2.518	0.591	1.628	0.830	0.820
196.2	2.260	1.453	854.2	503.1	20.34%	32.93%	1.923	0.391	1.577	0.836	0.772
196.2	2.273	0.829	462.2	893.6	20.08%	27.54%	1.513	0.267	1.223	0.908	0.747
196.2	4.376	1.500	829.7	529.1	21.79%	29.90%	1.531	0.255	1.545	0.840	0.692
196.1	4.369	0.800	441.6	914.0	21.96%	26.43%	1.277	0.155	1.210	0.912	0.700
196.0	6.412	0.803	448.5	907.1	22.74%	26.07%	1.198	0.111	1.214	0.910	0.695
196.0	6.428	1.578	881.4	477.2	22.71%	29.21%	1.404	0.197	1.613	0.831	0.660

Table B.5. Separation results for IMTL membrane 1226678-1-1: 25% Ar in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.0	1.038	0.648	325.5	96.7	21.27%	37.96%	2.264	0.384	1.911	0.929	0.857
23.1	1.039	0.646	335.2	490.5	18.49%	29.30%	1.827	0.383	1.283	0.927	0.839
23.2	1.045	0.666	349.7	1454.5	17.39%	26.66%	1.727	0.389	1.112	0.923	0.842
23.3	1.051	0.761	405.8	2356.8	16.78%	26.22%	1.763	0.420	1.082	0.912	0.852
23.2	1.115	2.081	1095.3	1666.3	17.19%	30.04%	2.068	0.651	1.274	0.779	0.764
23.5	3.752	2.167	1060.2	1541.8	20.17%	28.53%	1.581	0.366	1.284	0.786	0.727
23.5	4.912	0.986	526.5	2236.3	21.31%	25.57%	1.269	0.167	1.109	0.887	0.755
23.4	4.909	0.928	492.9	1459.4	21.57%	25.82%	1.266	0.159	1.153	0.894	0.750
23.5	4.910	0.904	476.0	494.0	22.20%	27.17%	1.307	0.155	1.375	0.897	0.740
23.4	4.910	0.872	452.4	173.6	23.04%	29.16%	1.375	0.151	1.775	0.902	0.718
23.5	6.396	0.561	294.3	1078.8	22.96%	25.23%	1.132	0.081	1.125	0.935	0.720
23.5	6.387	1.290	689.9	685.9	22.27%	27.25%	1.307	0.168	1.388	0.855	0.712
23.6	6.443	1.886	1001.0	372.6	22.71%	30.25%	1.476	0.226	1.790	0.796	0.682
23.6	3.440	2.359	1197.9	171.6	22.92%	38.01%	2.062	0.407	2.375	0.761	0.668
23.6	3.426	1.829	949.8	425.1	21.44%	32.40%	1.756	0.348	1.699	0.806	0.734
23.6	3.409	0.952	497.8	878.1	20.95%	26.96%	1.393	0.218	1.241	0.893	0.751
23.6	3.413	0.390	199.9	1175.3	22.27%	25.19%	1.175	0.103	1.081	0.956	0.765
23.7	1.051	0.595	295.9	114.0	20.87%	35.28%	2.067	0.362	1.773	0.935	0.823
25.0	1.052	0.598	297.0	112.8	20.88%	35.41%	2.077	0.363	1.780	0.935	0.826
93.4	1.054	0.668	290.8	117.8	20.60%	35.80%	2.149	0.388	1.748	0.944	0.830
89.9	1.054	0.668	291.6	116.8	20.64%	35.88%	2.152	0.388	1.753	0.944	0.830
89.2	1.054	0.668	292.8	115.9	20.66%	35.98%	2.158	0.388	1.759	0.943	0.832
93.5	1.054	0.671	292.5	116.0	20.66%	36.01%	2.161	0.389	1.758	0.944	0.832
95.8	1.055	0.687	310.7	721.0	17.80%	28.06%	1.800	0.394	1.190	0.941	0.839
95.1	1.062	0.804	370.2	1290.0	16.99%	27.26%	1.830	0.431	1.131	0.930	0.847
93.4	1.054	0.664	296.2	313.1	18.93%	30.76%	1.902	0.387	1.370	0.943	0.836
89.8	1.573	2.759	1210.5	162.7	22.06%	48.12%	3.278	0.637	2.420	0.786	0.870
90.7	1.575	2.809	1260.4	397.4	20.42%	40.36%	2.637	0.641	1.879	0.779	0.808

Table B.5. Separation results for IMTL membrane 1226678-1-1: 25% Ar in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
92.3	1.575	2.858	1318.8	1340.1	18.29%	31.89%	2.092	0.645	1.381	0.770	0.736
95.7	3.396	2.902	1313.6	525.4	21.25%	34.63%	1.964	0.461	1.754	0.772	0.714
95.9	3.413	2.887	1292.8	308.7	22.04%	37.68%	2.139	0.458	2.039	0.775	0.727
95.2	3.439	2.951	1359.1	1293.7	20.04%	30.36%	1.739	0.462	1.402	0.765	0.690
91.5	5.057	2.620	1187.7	182.7	23.19%	36.73%	1.922	0.341	2.325	0.790	0.680
90.1	5.029	2.613	1209.3	589.9	21.76%	31.77%	1.675	0.342	1.659	0.786	0.700
91.4	5.051	2.644	1241.2	1269.7	20.89%	29.05%	1.551	0.344	1.379	0.782	0.687
95.5	5.041	2.616	1216.5	797.8	21.37%	30.60%	1.622	0.342	1.534	0.787	0.698
95.5	6.703	1.873	866.4	510.4	22.38%	29.40%	1.445	0.218	1.577	0.843	0.708
91.3	6.709	2.519	1162.6	210.0	23.38%	33.99%	1.687	0.273	2.216	0.794	0.662
90.0	6.688	2.540	1204.1	1165.8	21.64%	28.52%	1.444	0.275	1.396	0.787	0.680
91.8	6.627	0.969	452.4	921.7	22.52%	26.19%	1.221	0.128	1.213	0.914	0.723
94.4	6.644	1.025	483.4	1609.6	22.22%	25.82%	1.219	0.134	1.137	0.909	0.732
95.8	6.654	1.059	498.6	2281.2	22.04%	25.63%	1.219	0.137	1.102	0.907	0.737
93.9	6.644	0.989	454.4	137.8	23.70%	29.23%	1.330	0.130	1.900	0.914	0.678
196.0	1.080	2.084	1151.6	512.7	19.06%	39.38%	2.759	0.659	1.702	0.824	0.881
196.0	1.052	1.155	658.3	1009.0	17.22%	30.32%	2.092	0.523	1.272	0.895	0.847
196.0	2.419	0.995	557.8	1108.4	19.90%	27.57%	1.532	0.291	1.218	0.911	0.762
196.0	2.445	2.054	1137.0	529.4	20.59%	34.81%	2.060	0.457	1.681	0.826	0.773
196.0	4.182	2.100	1166.8	498.1	21.81%	32.70%	1.742	0.334	1.722	0.822	0.725
196.0	4.239	0.982	569.2	1084.4	21.47%	26.91%	1.346	0.188	1.226	0.909	0.765
196.0	6.486	0.969	549.8	1114.9	22.48%	26.20%	1.224	0.130	1.214	0.912	0.719
195.9	6.504	2.079	1169.3	495.5	22.64%	30.68%	1.512	0.242	1.725	0.822	0.689

Table B.6. Separation results for IMTL membrane 1230530-89: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
19.4	1.053	3.504	303.5	73.8	21.12%	40.30%	2.521	0.769	2.029	0.933	0.572
19.4	1.054	3.502	308.6	296.1	18.85%	31.08%	1.942	0.769	1.399	0.932	0.514
19.4	1.054	3.524	313.2	1119.5	17.53%	26.89%	1.731	0.770	1.128	0.931	0.495
19.4	1.094	6.881	595.2	133.7	21.33%	39.82%	2.440	0.863	2.077	0.873	0.504
19.5	1.094	6.892	607.2	554.0	19.10%	30.97%	1.901	0.863	1.415	0.870	0.464
19.4	1.094	6.889	612.6	1303.5	18.21%	27.92%	1.739	0.863	1.205	0.869	0.448
19.5	4.067	4.236	368.9	90.9	22.42%	34.48%	1.820	0.510	2.020	0.919	0.474
19.4	4.068	4.248	372.5	186.0	21.53%	31.40%	1.669	0.511	1.649	0.918	0.473
19.6	4.069	4.270	375.5	370.1	20.76%	28.92%	1.553	0.512	1.391	0.918	0.463
19.5	4.081	4.287	381.7	1529.7	19.86%	26.12%	1.427	0.512	1.116	0.916	0.446
19.6	6.758	5.139	464.1	1449.6	20.86%	26.15%	1.343	0.432	1.145	0.899	0.422
19.6	6.759	5.119	459.6	468.6	21.51%	28.07%	1.424	0.431	1.380	0.900	0.433
19.6	6.760	5.093	451.6	125.5	22.87%	32.04%	1.589	0.430	1.950	0.902	0.427
19.5	1.056	3.495	300.0	82.7	20.94%	39.12%	2.426	0.768	1.955	0.934	0.557
86.6	1.012	3.492	268.1	94.0	19.59%	39.77%	2.710	0.775	1.821	0.948	0.698
88.2	1.012	3.500	274.0	266.2	17.63%	32.19%	2.218	0.776	1.395	0.947	0.650
87.7	1.013	3.517	280.4	1056.6	16.09%	27.21%	1.949	0.776	1.122	0.946	0.630
87.9	1.032	6.806	522.9	129.1	20.28%	42.84%	2.946	0.868	2.019	0.902	0.673
89.6	1.032	6.813	536.4	512.3	17.75%	32.18%	2.199	0.868	1.401	0.900	0.599
89.5	1.033	6.824	544.3	1371.6	16.58%	28.14%	1.970	0.869	1.176	0.898	0.578
88.8	4.105	3.736	287.7	89.1	21.72%	35.10%	1.949	0.476	1.888	0.945	0.611
90.0	4.105	3.741	292.3	284.4	20.10%	29.82%	1.689	0.477	1.395	0.944	0.600
89.5	4.103	3.750	296.7	1125.1	19.06%	26.47%	1.528	0.478	1.122	0.943	0.572
86.8	6.864	5.075	409.4	1035.1	20.02%	26.84%	1.466	0.425	1.176	0.922	0.553
87.4	6.865	5.049	403.7	409.3	20.72%	28.93%	1.557	0.424	1.382	0.923	0.564
86.5	6.866	5.026	396.3	116.5	22.32%	33.68%	1.767	0.423	1.918	0.924	0.560
88.9	1.030	3.483	266.7	89.1	19.68%	40.23%	2.747	0.772	1.847	0.949	0.706
152.1	1.052	3.520	249.7	75.2	19.48%	42.75%	3.087	0.770	1.904	0.957	0.814
152.2	1.054	3.526	256.8	235.1	17.14%	33.39%	2.424	0.770	1.414	0.955	0.749

Table B.6. Separation results for IMTL membrane 1230530-89: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
151.3	1.054	3.550	264.4	931.8	15.46%	27.64%	2.090	0.771	1.130	0.954	0.717
150.2	1.114	6.752	485.7	128.1	19.70%	43.94%	3.195	0.858	1.980	0.917	0.770
151.7	1.114	6.769	500.7	465.7	17.17%	33.15%	2.393	0.859	1.409	0.915	0.688
152.9	1.115	6.776	509.6	1398.7	15.76%	28.27%	2.106	0.859	1.163	0.914	0.663
151.2	4.035	3.506	249.9	71.7	21.63%	36.56%	2.088	0.465	1.932	0.957	0.693
152.4	4.035	3.534	256.9	235.6	19.78%	30.57%	1.785	0.467	1.414	0.955	0.681
151.0	4.035	3.566	263.3	962.8	18.51%	26.74%	1.606	0.469	1.126	0.954	0.658
150.5	6.654	4.926	371.5	1536.9	19.21%	26.38%	1.507	0.425	1.112	0.936	0.626
151.7	6.654	4.896	364.4	372.9	20.25%	29.49%	1.647	0.424	1.379	0.937	0.646
151.0	6.657	4.889	356.1	95.1	22.17%	35.53%	1.934	0.423	1.973	0.939	0.652
152.8	1.078	3.452	246.2	69.9	19.64%	43.19%	3.110	0.762	1.938	0.957	0.816

Table B.7. Separation results for IMTL membrane 1230530-89: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
22.7	1.045	3.543	287.3	69.1	21.99%	36.45%	2.034	0.772	2.036	0.919	0.249
22.7	1.046	3.547	292.4	271.5	20.21%	29.76%	1.672	0.772	1.410	0.918	0.234
22.7	1.045	3.568	297.6	1061.0	19.14%	26.49%	1.523	0.773	1.129	0.917	0.227
22.7	1.035	6.924	550.9	131.5	22.51%	34.51%	1.815	0.870	2.040	0.851	0.188
22.7	1.034	6.924	563.4	795.0	20.56%	27.92%	1.497	0.870	1.292	0.848	0.182
22.7	1.034	6.924	565.2	1036.5	20.36%	27.35%	1.473	0.870	1.233	0.847	0.181
22.8	4.450	3.592	284.4	75.6	23.51%	30.19%	1.407	0.447	1.976	0.920	0.175
22.8	4.445	3.590	286.6	268.7	22.65%	27.45%	1.292	0.447	1.406	0.919	0.176
22.8	4.448	3.599	289.1	1068.2	22.01%	25.75%	1.229	0.447	1.125	0.919	0.173
22.9	6.915	4.473	348.8	112.4	23.92%	28.21%	1.250	0.393	1.867	0.903	0.131
22.8	6.915	4.456	349.2	332.7	23.40%	26.66%	1.190	0.392	1.401	0.903	0.133
22.8	6.914	4.450	351.5	1248.1	22.97%	25.56%	1.152	0.392	1.129	0.902	0.132
22.8	1.127	3.489	280.0	78.3	21.94%	35.55%	1.963	0.756	1.946	0.921	0.247
90.1	1.128	3.396	244.8	79.6	19.75%	40.18%	2.729	0.751	1.862	0.940	0.458
90.2	1.132	3.417	253.4	241.0	17.71%	32.41%	2.228	0.751	1.402	0.938	0.433
89.3	1.134	3.427	259.1	717.1	16.46%	28.04%	1.977	0.751	1.162	0.937	0.416
87.9	1.049	6.666	496.7	478.1	17.88%	32.10%	2.172	0.864	1.398	0.882	0.383
87.4	1.050	6.671	503.9	1096.2	16.90%	28.67%	1.976	0.864	1.201	0.880	0.372
90.0	1.049	6.627	480.1	162.9	19.71%	39.59%	2.669	0.863	1.839	0.886	0.413
91.0	6.624	4.869	356.9	282.6	21.18%	29.74%	1.576	0.424	1.463	0.914	0.354
88.5	6.626	4.848	361.0	894.3	20.26%	26.93%	1.450	0.423	1.179	0.913	0.345
89.9	6.627	4.829	350.6	130.1	22.17%	32.33%	1.677	0.422	1.792	0.915	0.341
89.9	1.095	6.924	509.9	115.7	20.62%	42.75%	2.876	0.863	2.071	0.879	0.415

Table B.7. Separation results for IMTL membrane 1230530-89: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
140.7	1.085	3.550	238.2	81.4	18.66%	42.06%	3.164	0.766	1.835	0.946	0.566
138.5	1.086	3.537	245.7	209.9	16.73%	34.09%	2.575	0.765	1.437	0.945	0.528
137.9	1.087	3.542	252.3	707.2	15.14%	28.32%	2.215	0.765	1.160	0.943	0.505
143.0	1.154	6.924	488.4	433.3	16.74%	33.67%	2.524	0.857	1.424	0.894	0.486
142.8	1.154	6.924	498.0	1106.0	15.49%	29.02%	2.230	0.857	1.197	0.892	0.468
137.9	1.152	6.924	473.4	144.9	19.05%	42.72%	3.169	0.857	1.895	0.896	0.519
138.0	6.808	5.679	394.2	350.4	20.03%	30.27%	1.733	0.455	1.424	0.913	0.432
139.6	6.809	5.673	399.7	1037.1	19.01%	27.19%	1.591	0.454	1.172	0.912	0.424
144.3	6.811	5.649	380.7	129.6	21.47%	34.77%	1.950	0.453	1.837	0.916	0.433
144.1	1.103	3.540	237.1	83.3	18.62%	42.00%	3.166	0.762	1.821	0.947	0.573

Table B.8. Separation results for IMTL membrane 1230530-89: 24.97% C_3H_8 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
22.5	1.047	3.472	242.1	77.5	24.43%	26.73%	1.129	0.768	1.870	0.918	0.026
22.5	1.048	3.476	241.3	240.7	24.20%	25.69%	1.083	0.768	1.387	0.918	0.023
22.5	1.048	3.489	241.2	736.2	24.01%	25.24%	1.069	0.769	1.148	0.918	0.023
22.5	1.028	1.095	85.4	186.5	22.71%	25.96%	1.194	0.516	1.200	0.970	0.087
22.5	1.067	6.757	379.3	145.7	25.68%	22.87%	0.858	0.864	1.774	0.874	-0.029
22.5	1.067	6.775	373.6	387.8	26.26%	23.61%	0.868	0.864	1.375	0.876	-0.034
22.4	1.066	6.787	370.5	1021.6	26.66%	24.30%	0.883	0.864	1.163	0.877	-0.036
22.5	4.055	4.521	244.8	103.0	26.09%	22.03%	0.800	0.527	1.729	0.917	-0.065
22.5	4.055	4.517	239.8	246.2	26.93%	22.89%	0.806	0.527	1.378	0.918	-0.079
22.5	4.055	4.522	235.7	734.1	27.74%	23.98%	0.822	0.527	1.146	0.920	-0.087
22.6	6.680	5.305	226.3	259.3	28.32%	21.88%	0.709	0.443	1.346	0.923	-0.144
22.6	6.680	5.285	217.1	754.8	29.71%	23.48%	0.726	0.442	1.132	0.926	-0.161
22.6	6.682	5.277	230.5	137.9	27.35%	21.06%	0.709	0.441	1.571	0.922	-0.124
22.6	6.675	2.321	113.9	250.6	27.05%	24.02%	0.853	0.258	1.199	0.960	-0.134
22.4	1.089	10.240	440.1	950.9	29.41%	22.86%	0.711	0.904	1.202	0.855	-0.084
86.0	0.994	3.542	248.3	65.0	20.86%	39.78%	2.507	0.781	1.985	0.926	0.284
87.7	0.995	3.553	255.3	212.1	18.67%	32.23%	2.071	0.781	1.447	0.925	0.278
88.1	0.995	3.544	259.4	629.2	17.42%	28.03%	1.846	0.781	1.183	0.924	0.269
86.3	1.004	6.924	466.0	113.9	21.52%	38.28%	2.262	0.873	2.025	0.867	0.223
86.1	1.004	6.924	481.3	405.5	19.50%	31.25%	1.877	0.873	1.442	0.862	0.219
86.4	1.004	6.924	488.6	899.7	18.59%	28.36%	1.734	0.873	1.233	0.861	0.215
89.2	4.064	6.575	436.5	122.5	22.53%	33.22%	1.711	0.618	1.944	0.875	0.183
88.1	4.064	6.569	444.2	400.5	21.19%	29.15%	1.531	0.618	1.419	0.873	0.188
87.0	4.063	6.570	448.3	939.1	20.53%	27.08%	1.438	0.618	1.208	0.871	0.182
88.0	1.052	3.445	240.6	71.0	20.61%	38.93%	2.456	0.766	1.916	0.929	0.289
137.6	0.993	3.446	224.7	56.3	19.57%	45.16%	3.384	0.776	2.010	0.939	0.441
136.9	0.994	3.445	233.9	178.6	17.02%	34.90%	2.615	0.776	1.476	0.937	0.408
137.4	0.994	3.456	241.1	590.0	15.31%	28.77%	2.234	0.777	1.181	0.935	0.390
138.8	1.001	6.661	448.8	383.7	17.10%	33.68%	2.463	0.869	1.437	0.882	0.360
139.8	1.001	6.669	458.2	933.6	15.84%	29.32%	2.204	0.869	1.213	0.880	0.352

Table B.8. Separation results for IMTL membrane 1230530-89: 24.97% C_3H_8 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
143.0	1.001	6.617	427.7	115.1	19.53%	43.53%	3.176	0.869	1.968	0.888	0.388
146.3	4.153	6.712	428.9	112.6	21.22%	38.49%	2.323	0.618	1.983	0.888	0.329
147.1	4.148	6.718	442.6	370.4	19.06%	31.87%	1.986	0.618	1.444	0.885	0.338
147.2	4.148	6.709	449.9	937.1	17.95%	28.31%	1.806	0.618	1.209	0.883	0.331
145.4	1.041	3.504	225.5	50.4	19.79%	46.53%	3.528	0.771	2.080	0.940	0.455
209.1	1.000	3.525	283.3	83.5	18.88%	43.46%	3.302	0.779	1.916	0.931	0.449
209.5	1.000	3.528	294.9	235.9	16.90%	34.36%	2.573	0.779	1.460	0.929	0.404
210.0	1.007	3.541	493.3	553.8	19.31%	29.78%	1.772	0.779	1.352	0.884	0.225
211.4	1.008	3.461	472.6	65.2	21.60%	47.01%	3.220	0.774	2.402	0.889	0.364
212.2	1.009	2.826	530.4	105.1	21.84%	39.86%	2.371	0.737	2.156	0.876	0.267
212.4	1.010	2.854	542.4	479.4	20.70%	29.64%	1.615	0.739	1.426	0.873	0.181
212.8	3.440	3.010	699.6	210.7	22.68%	32.29%	1.625	0.467	1.904	0.840	0.227
212.9	3.444	3.047	712.6	665.9	22.09%	28.01%	1.372	0.469	1.408	0.837	0.182
213.2	6.700	2.287	658.6	174.4	23.67%	29.81%	1.370	0.255	1.978	0.849	0.235
213.3	6.706	2.330	682.7	628.7	23.13%	26.92%	1.224	0.258	1.412	0.843	0.198
213.5	1.020	3.493	667.5	171.6	21.60%	37.24%	2.154	0.774	1.995	0.847	0.239
213.7	0.999	1.393	258.5	106.7	21.35%	33.49%	1.854	0.582	1.738	0.938	0.244

Table B.9. Separation results for IMTL membrane 1230530-89: 25% CO_2 in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
22.0	1.061	4.406	259.8	314.1	23.95%	28.65%	1.276	0.806	1.331	0.929	0.119
22.0	1.062	4.456	263.3	1222.7	23.28%	26.98%	1.218	0.808	1.101	0.928	0.114
22.0	1.061	4.421	259.0	65.4	25.06%	32.93%	1.469	0.806	2.005	0.929	0.135
22.0	1.018	3.498	206.3	58.3	24.79%	32.66%	1.472	0.775	1.940	0.943	0.144
22.0	1.019	3.544	210.1	208.0	23.72%	29.03%	1.315	0.777	1.389	0.942	0.134
22.1	1.018	3.568	212.6	825.5	22.92%	26.99%	1.243	0.778	1.119	0.941	0.128
22.1	1.052	6.860	399.1	1456.2	23.50%	26.84%	1.194	0.867	1.126	0.892	0.096
22.1	1.052	6.802	394.5	411.8	23.95%	28.26%	1.251	0.866	1.373	0.893	0.102
22.0	1.053	6.783	392.0	100.1	24.80%	31.75%	1.411	0.866	1.999	0.894	0.115
22.0	0.992	1.672	101.0	418.8	22.72%	26.70%	1.239	0.628	1.112	0.972	0.152
22.1	0.992	1.661	100.2	100.4	23.35%	28.61%	1.315	0.626	1.386	0.972	0.162
22.1	0.992	1.588	95.7	44.3	23.94%	30.51%	1.395	0.616	1.684	0.973	0.169
22.2	3.427	6.722	383.5	396.7	24.37%	27.14%	1.156	0.662	1.376	0.896	0.082
22.1	3.424	6.747	385.7	1473.3	23.97%	26.14%	1.123	0.663	1.121	0.896	0.079
22.1	3.427	6.730	382.4	117.7	24.80%	28.95%	1.236	0.663	1.892	0.897	0.091
22.2	3.421	3.586	208.4	778.2	23.68%	26.05%	1.135	0.512	1.123	0.942	0.108
22.1	3.422	3.575	207.2	211.5	24.06%	27.06%	1.171	0.511	1.380	0.943	0.111
22.2	3.424	3.556	205.5	73.4	24.45%	28.61%	1.238	0.509	1.812	0.943	0.118
22.3	6.675	3.507	199.6	943.8	24.42%	25.62%	1.066	0.344	1.099	0.945	0.080
22.3	6.677	3.467	197.2	221.9	24.64%	26.06%	1.078	0.342	1.351	0.945	0.077
22.2	6.678	4.858	273.6	135.9	24.68%	26.63%	1.108	0.421	1.651	0.925	0.072
22.2	6.679	4.863	273.5	312.2	24.44%	26.02%	1.087	0.421	1.347	0.925	0.072
22.2	6.678	4.869	274.6	1180.0	24.17%	25.44%	1.071	0.422	1.108	0.925	0.071
22.1	1.208	5.726	333.6	1413.6	22.03%	25.89%	1.236	0.826	1.110	0.909	0.122
22.2	1.207	5.715	331.9	337.5	22.61%	27.62%	1.306	0.826	1.381	0.910	0.127
22.2	1.207	5.695	329.5	105.5	23.34%	30.51%	1.443	0.825	1.870	0.910	0.136
85.3	1.003	2.175	119.6	457.9	17.90%	26.81%	1.680	0.684	1.121	0.970	0.394
86.1	1.003	2.142	116.6	118.4	19.13%	30.69%	1.872	0.681	1.382	0.971	0.412
89.3	1.003	2.127	113.3	36.2	20.94%	38.06%	2.320	0.680	1.871	0.972	0.461
87.1	1.016	4.286	236.0	978.2	17.36%	26.79%	1.742	0.808	1.112	0.943	0.378
86.6	1.017	4.255	232.0	231.2	18.75%	31.11%	1.956	0.807	1.387	0.944	0.391

Table B.9. Separation results for IMTL membrane 1230530-89: 25% CO_2 in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
90.5	1.016	4.216	224.9	67.2	20.64%	39.56%	2.517	0.806	1.909	0.946	0.450
90.8	1.034	6.862	375.0	1162.3	17.56%	27.11%	1.746	0.869	1.146	0.911	0.355
89.4	1.032	6.695	362.1	321.9	18.94%	31.63%	1.981	0.866	1.424	0.914	0.376
88.2	1.032	6.678	354.9	83.2	21.15%	41.06%	2.597	0.866	2.050	0.915	0.424
90.7	3.423	4.039	219.1	810.5	19.55%	26.40%	1.476	0.541	1.124	0.947	0.356
90.1	3.423	4.005	214.5	209.1	20.51%	29.45%	1.617	0.539	1.394	0.948	0.374
87.2	3.384	6.794	371.4	1361.3	19.18%	26.54%	1.522	0.668	1.125	0.911	0.329
87.4	3.389	6.804	368.4	343.5	20.26%	29.97%	1.684	0.668	1.408	0.912	0.344
87.0	3.397	6.779	361.3	89.6	22.10%	36.80%	2.053	0.666	2.017	0.914	0.370
89.4	6.698	4.488	243.5	909.0	21.03%	26.02%	1.321	0.401	1.123	0.941	0.327
89.3	6.700	4.447	238.9	240.3	21.77%	28.10%	1.404	0.399	1.384	0.942	0.335
90.5	6.702	4.422	235.0	64.6	23.12%	31.87%	1.556	0.398	1.956	0.943	0.327
146.2	6.701	4.490	223.3	83.2	22.07%	33.12%	1.749	0.401	1.790	0.951	0.474
146.8	6.702	4.486	225.1	190.0	21.00%	29.88%	1.603	0.401	1.441	0.950	0.474
145.4	6.702	4.479	228.1	915.6	19.78%	26.31%	1.449	0.401	1.115	0.950	0.456
142.1	3.453	6.677	334.0	95.6	20.91%	39.43%	2.462	0.659	1.933	0.927	0.534
140.5	3.453	6.724	344.5	329.7	18.94%	31.38%	1.957	0.661	1.400	0.924	0.483
146.6	3.455	6.773	349.7	1317.5	17.56%	27.03%	1.739	0.662	1.122	0.924	0.465
147.6	3.452	3.543	177.4	171.7	19.62%	30.62%	1.808	0.507	1.396	0.961	0.513
146.5	3.452	3.531	179.6	678.7	18.57%	26.78%	1.603	0.506	1.122	0.960	0.478
146.2	1.048	6.731	334.6	84.3	19.97%	45.38%	3.330	0.865	2.007	0.927	0.624
140.0	1.050	6.768	348.4	314.2	17.61%	33.29%	2.335	0.866	1.419	0.924	0.508
142.2	1.050	6.775	353.7	1209.3	15.99%	27.70%	2.013	0.866	1.134	0.923	0.483
145.6	1.027	4.118	205.4	72.6	19.25%	41.65%	2.994	0.800	1.817	0.955	0.620
145.8	1.027	4.102	209.0	198.5	17.31%	33.18%	2.372	0.800	1.402	0.954	0.554
147.1	1.027	4.094	212.5	786.2	15.69%	27.54%	2.042	0.800	1.124	0.953	0.525
145.7	1.008	1.934	95.5	35.5	19.87%	39.50%	2.633	0.657	1.791	0.979	0.612
145.1	1.009	1.946	98.1	90.2	18.06%	32.68%	2.202	0.659	1.413	0.978	0.570
141.1	1.009	1.941	100.3	379.6	16.50%	27.23%	1.893	0.658	1.122	0.977	0.534

Table B.10. Separation results for IMTL membrane 1230530-89: 25% Ar in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
23.7	1.974	2.213	127.3	267.6	17.92%	28.39%	1.816	0.529	1.207	0.971	0.609
23.8	1.018	3.428	199.9	195.6	16.77%	33.40%	2.488	0.771	1.393	0.956	0.670
23.7	1.017	3.445	205.9	802.8	15.08%	27.35%	2.119	0.772	1.119	0.954	0.628
23.6	1.052	6.691	392.8	215.9	17.76%	38.20%	2.862	0.864	1.606	0.915	0.678
23.7	1.052	6.710	398.5	369.9	16.75%	33.72%	2.528	0.864	1.410	0.913	0.635
23.8	1.091	6.711	408.7	1660.8	15.09%	27.22%	2.106	0.860	1.114	0.911	0.586
23.7	3.427	6.816	411.7	1656.4	16.79%	26.80%	1.814	0.665	1.115	0.911	0.557
23.8	3.427	6.811	404.4	365.9	18.35%	32.15%	2.107	0.665	1.418	0.912	0.595
23.9	3.427	6.783	395.2	144.2	20.03%	38.63%	2.513	0.664	1.801	0.914	0.640
23.9	3.412	3.674	209.9	74.8	20.86%	37.15%	2.242	0.519	1.813	0.953	0.641
23.8	3.413	3.700	215.1	198.7	19.16%	31.32%	1.923	0.520	1.411	0.952	0.611
23.9	3.411	3.708	219.6	1414.4	17.51%	26.01%	1.655	0.521	1.074	0.951	0.570
23.8	6.835	5.123	307.1	1397.9	19.00%	26.18%	1.512	0.428	1.103	0.933	0.538
23.9	6.836	5.112	302.4	316.7	20.09%	29.50%	1.665	0.428	1.372	0.934	0.561
23.9	6.836	5.062	295.0	117.2	21.63%	33.81%	1.851	0.425	1.757	0.935	0.563
24.0	1.089	6.718	390.4	140.0	18.95%	42.63%	3.178	0.861	1.809	0.915	0.707
24.0	1.090	6.782	411.4	1655.7	15.42%	27.49%	2.080	0.861	1.115	0.911	0.571
84.4	1.050	1.687	84.5	80.0	17.22%	33.37%	2.407	0.616	1.403	0.983	0.765
82.0	1.049	1.650	80.4	26.0	19.73%	42.18%	2.969	0.611	1.865	0.984	0.811
84.5	1.050	1.724	88.6	454.8	15.31%	26.84%	2.029	0.621	1.092	0.982	0.714
84.5	1.050	1.748	90.5	784.6	14.76%	25.86%	2.014	0.625	1.056	0.982	0.724
85.0	1.068	3.562	186.7	688.5	14.23%	27.62%	2.299	0.769	1.125	0.963	0.721
83.6	1.067	3.489	178.7	157.3	16.08%	34.72%	2.776	0.766	1.427	0.965	0.779
81.9	1.066	3.473	172.1	46.7	18.80%	47.24%	3.867	0.765	1.964	0.966	0.914
83.2	1.067	3.541	186.8	1177.7	14.01%	26.44%	2.207	0.768	1.075	0.963	0.701
84.5	1.092	6.834	363.5	1351.4	14.15%	27.56%	2.308	0.862	1.124	0.930	0.672
83.0	1.092	6.797	353.2	343.7	15.73%	34.04%	2.765	0.862	1.395	0.931	0.729
81.7	1.091	6.786	340.8	87.0	18.73%	48.67%	4.113	0.862	1.999	0.933	0.896
81.9	3.477	6.554	346.2	1301.1	16.07%	27.09%	1.941	0.653	1.123	0.933	0.636
83.4	3.481	5.017	262.3	1382.3	16.09%	26.36%	1.866	0.590	1.089	0.949	0.657
84.8	3.486	5.045	257.7	229.5	17.84%	32.43%	2.211	0.591	1.423	0.950	0.701

Table B.10. Separation results for IMTL membrane 1230530-89: 25% Ar in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
84.3	1.105	6.805	362.8	1287.4	14.39%	27.99%	2.311	0.860	1.129	0.930	0.672
82.4	1.105	6.791	355.1	353.0	15.96%	34.23%	2.740	0.860	1.388	0.931	0.724
81.7	1.104	6.775	338.7	72.2	19.49%	52.23%	4.516	0.860	2.110	0.934	0.960
81.5	3.084	6.708	356.3	1294.5	15.96%	27.57%	2.005	0.685	1.126	0.931	0.647
83.6	3.085	6.685	347.6	334.2	17.39%	33.04%	2.344	0.684	1.399	0.932	0.697
84.2	3.084	6.133	334.7	97.7	20.01%	43.85%	3.123	0.665	1.922	0.935	0.821
84.7	3.080	3.640	186.8	237.1	17.92%	30.73%	2.031	0.542	1.318	0.963	0.693
84.7	3.080	3.682	190.5	757.3	16.75%	27.14%	1.851	0.545	1.116	0.962	0.673
82.3	6.610	5.022	261.6	1046.2	18.35%	26.72%	1.623	0.432	1.116	0.949	0.630
82.1	6.611	4.961	255.5	263.2	19.58%	30.32%	1.787	0.429	1.377	0.950	0.649
85.0	6.611	4.946	249.5	117.2	20.84%	34.13%	1.968	0.428	1.677	0.951	0.656
147.9	1.002	1.457	69.1	70.5	16.91%	33.31%	2.454	0.593	1.380	0.988	0.833
144.7	1.002	1.497	73.6	606.4	14.78%	26.34%	2.062	0.599	1.058	0.987	0.785
146.2	1.020	3.473	174.6	705.1	13.74%	27.95%	2.434	0.773	1.115	0.969	0.795
148.6	1.019	3.417	166.7	165.6	15.55%	34.96%	2.920	0.770	1.388	0.970	0.856
149.9	1.019	3.416	161.0	57.6	17.87%	46.14%	3.935	0.770	1.811	0.971	1.002
150.1	1.050	6.884	349.8	1366.2	13.58%	28.05%	2.480	0.868	1.118	0.939	0.751
151.2	1.050	6.864	339.9	340.1	15.26%	35.07%	2.999	0.867	1.386	0.941	0.817
152.2	1.048	6.843	326.5	101.6	17.93%	48.92%	4.384	0.867	1.886	0.943	1.015
150.6	3.426	3.508	170.7	645.0	16.69%	27.29%	1.873	0.506	1.122	0.970	0.734
152.5	3.427	3.467	164.9	164.8	18.18%	32.08%	2.125	0.503	1.386	0.971	0.768
151.3	3.432	6.711	336.4	1394.5	15.46%	27.44%	2.067	0.662	1.112	0.941	0.713
150.7	3.435	6.662	327.2	349.8	16.89%	32.84%	2.406	0.660	1.366	0.943	0.765
152.5	3.435	6.633	314.7	101.1	19.37%	43.36%	3.187	0.659	1.869	0.945	0.869
150.9	6.720	4.810	235.2	1132.4	17.95%	26.55%	1.653	0.417	1.097	0.959	0.688
150.9	6.721	4.769	229.4	236.2	19.22%	30.64%	1.856	0.415	1.377	0.960	0.722
150.9	6.721	4.742	222.1	68.0	21.35%	37.12%	2.174	0.414	1.895	0.961	0.721

Table B.11. Separation results for IMTL membrane 1230530-108: 25.00% CH_4 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
22.0	0.982	6.812	7.6	179.3	18.67%	25.37%	1.481	0.874	1.021	0.998	0.295
22.2	3.277	6.924	8.7	176.9	19.91%	25.23%	1.358	0.679	1.024	0.998	0.282
21.2	6.520	6.309	9.5	177.8	21.39%	25.19%	1.237	0.492	1.026	0.998	0.258
95.1	0.992	6.569	7.0	77.9	17.45%	25.68%	1.635	0.869	1.044	0.999	0.384
91.5	5.036	6.924	8.5	77.9	19.84%	25.57%	1.388	0.579	1.053	0.998	0.349
148.5	4.197	6.875	7.4	173.9	17.99%	25.29%	1.543	0.621	1.021	0.999	0.469
144.6	1.127	6.706	7.0	173.5	15.77%	25.37%	1.816	0.856	1.020	0.999	0.512
209.1	0.995	6.831	10.7	171.4	12.47%	25.76%	2.435	0.873	1.031	0.998	0.874

Table B.12. Separation results for IMTL membrane 1230530-108: 25.02% C_2H_6 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
21.7	0.984	6.686	6.6	66.0	18.36%	25.73%	1.541	0.872	1.049	0.998	0.206
23.2	4.850	6.858	9.1	66.9	20.84%	25.51%	1.301	0.586	1.065	0.997	0.168
91.1	1.010	6.722	6.6	66.9	16.91%	25.84%	1.711	0.869	1.048	0.998	0.272
94.9	4.841	6.850	7.4	67.7	19.55%	25.63%	1.418	0.586	1.053	0.998	0.236
148.2	1.024	6.877	6.3	145.2	15.25%	25.88%	1.939	0.870	1.021	0.999	0.368
209.0	0.994	6.785	9.3	144.6	11.81%	25.78%	2.595	0.872	1.031	0.998	0.618

Table B.13. Separation results for IMTL membrane 1230530-108: 24.97% C_3H_8 in H_2

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
22.8	0.993	6.862	6.6	59.3	19.15%	25.57%	1.451	0.874	1.053	0.998	0.133
90.9	1.025	6.844	6.2	59.3	16.88%	25.80%	1.712	0.870	1.051	0.998	0.211
150.9	1.005	6.778	6.0	126.9	14.51%	25.47%	2.013	0.871	1.023	0.998	0.309
202.5	0.995	6.803	9.6	124.2	11.29%	26.00%	2.762	0.872	1.038	0.998	0.529

Table B.14. Separation results for IMTL membrane 1230530-108: 25% CO_2 in He

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
21.3	0.975	6.704	4.9	332.1	17.44%	25.11%	1.587	0.873	1.007	0.999	0.289
21.7	4.825	6.770	5.9	329.3	19.90%	25.12%	1.351	0.584	1.009	0.998	0.257
89.8	1.256	6.733	5.9	214.4	15.04%	25.22%	1.904	0.843	1.014	0.999	0.458
90.0	4.145	6.692	5.6	213.0	17.24%	25.20%	1.617	0.618	1.013	0.999	0.426
151.2	4.654	6.798	5.1	213.7	15.35%	25.25%	1.863	0.594	1.012	0.999	0.621
139.7	1.134	6.801	23.9	201.7	12.64%	25.28%	2.338	0.857	1.057	0.995	0.641
196.6	0.994	6.839	6.7	214.2	10.49%	25.40%	2.904	0.873	1.015	0.999	0.928

Table B.15. Separation results for IMTL membrane 1230530-108: 25% Ar in He.

T (ºC)	P_{LO} (bar)	dP (bar)	F_{LO} (sccm)	F_{HI} (sccm)	X_{LO} (mol % hvy)	X_{HI} (mol % hvy)	α	E_P	E_C	E_M	E_B
21.6	4.612	6.837	5.9	404.0	18.72%	25.09%	1.454	0.597	1.007	0.999	0.350
21.8	1.104	6.746	4.9	404.6	16.21%	25.11%	1.732	0.859	1.006	0.999	0.392
90.1	4.973	6.428	5.9	262.9	16.74%	25.19%	1.674	0.564	1.011	0.999	0.548
90.1	1.165	6.784	6.6	263.9	14.07%	25.18%	2.055	0.853	1.012	0.999	0.566
148.6	4.752	6.620	5.6	262.2	14.24%	25.23%	2.032	0.582	1.011	0.999	0.812
149.7	1.036	6.759	5.5	262.1	11.49%	25.28%	2.607	0.867	1.010	0.999	0.849
209.2	0.993	6.531	8.3	10.3	11.70%	35.75%	4.200	0.868	1.325	0.999	1.289
198.5	0.995	6.818	10.1	259.1	8.93%	25.57%	3.502	0.873	1.019	0.998	1.303

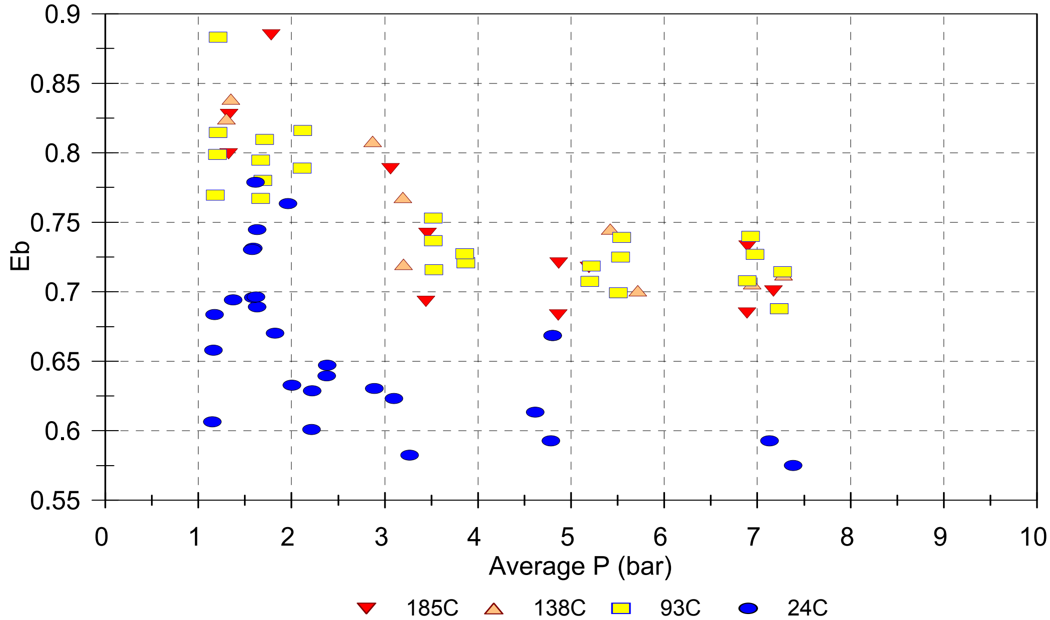

Fig. B.1. Membrane efficiency vs average pressure: Membrane 1226678-1-1, 25% CH_4 in H_2.

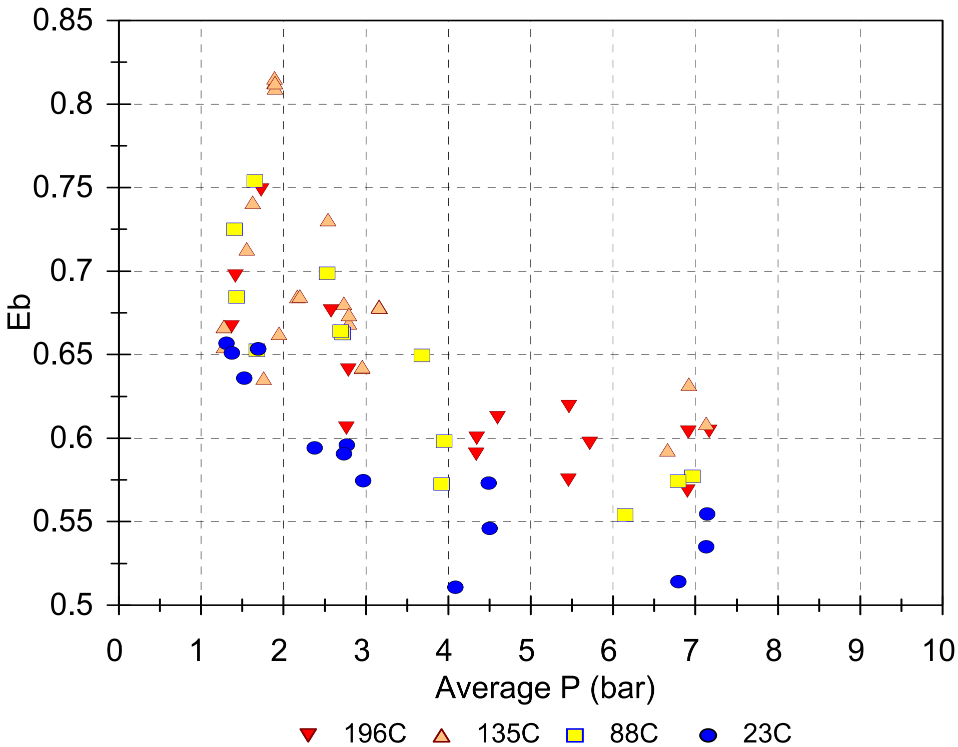

Fig. B.2. Membrane efficiency vs average pressure: Membrane 1226678-1-1, 25.02% C_2H_6 in H_2.

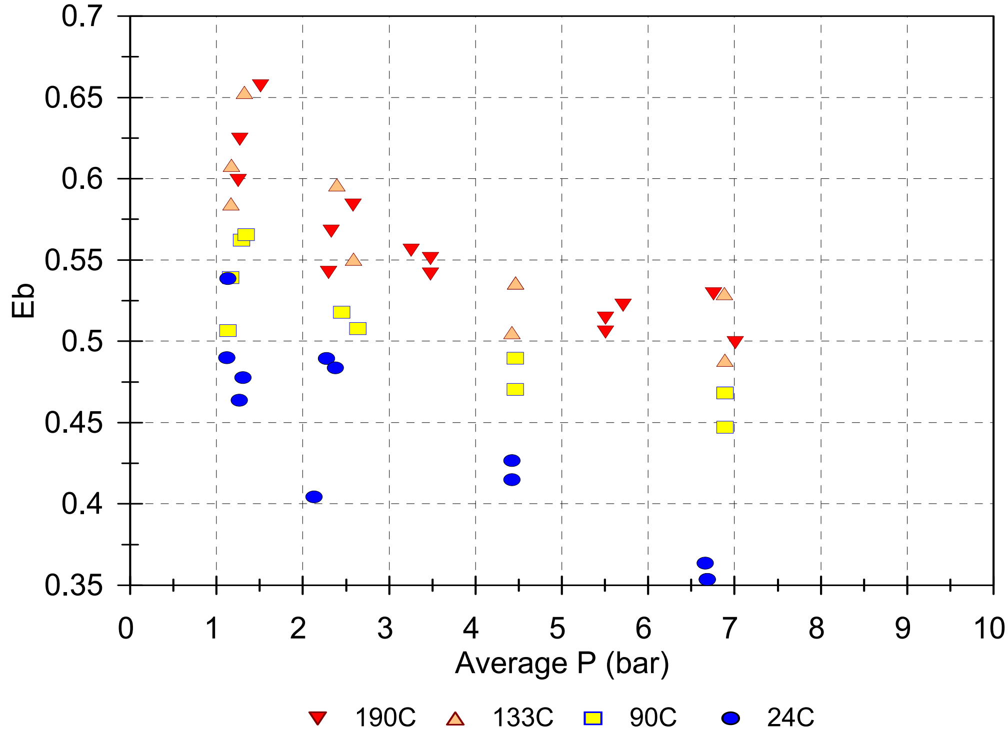

Fig. B.3. Membrane efficiency vs average pressure: Membrane 1226678-1-1, 24.97% C_3H_8 in H_2.

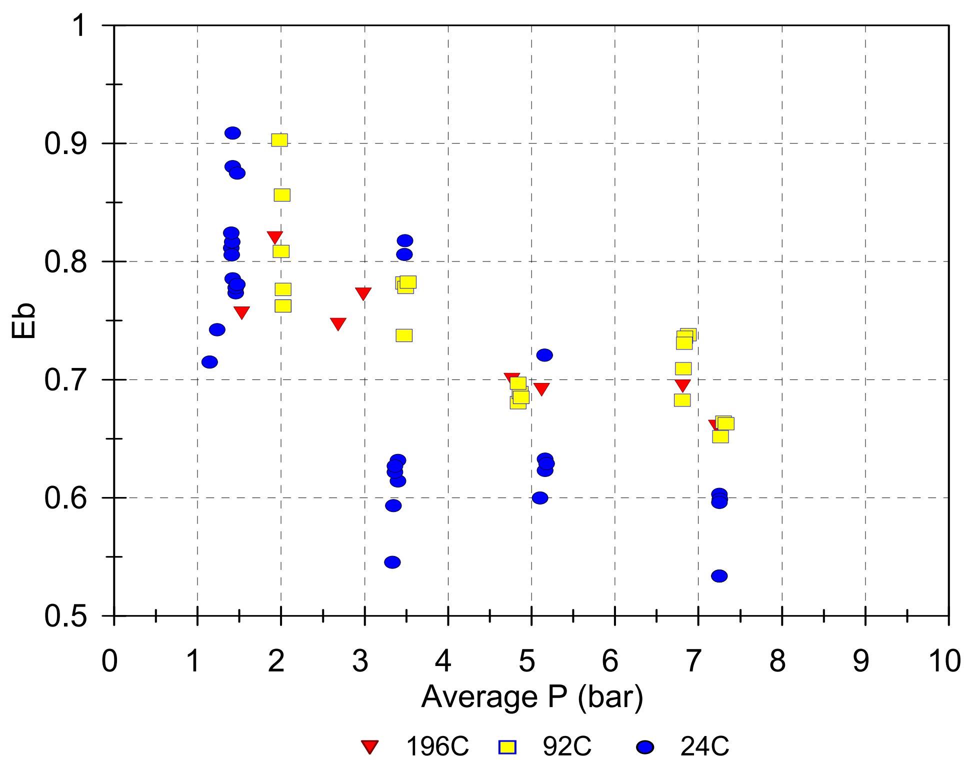

Fig. B.4. Membrane efficiency vs average pressure: Membrane 1226678-1-1, 25% CO_2 in He.

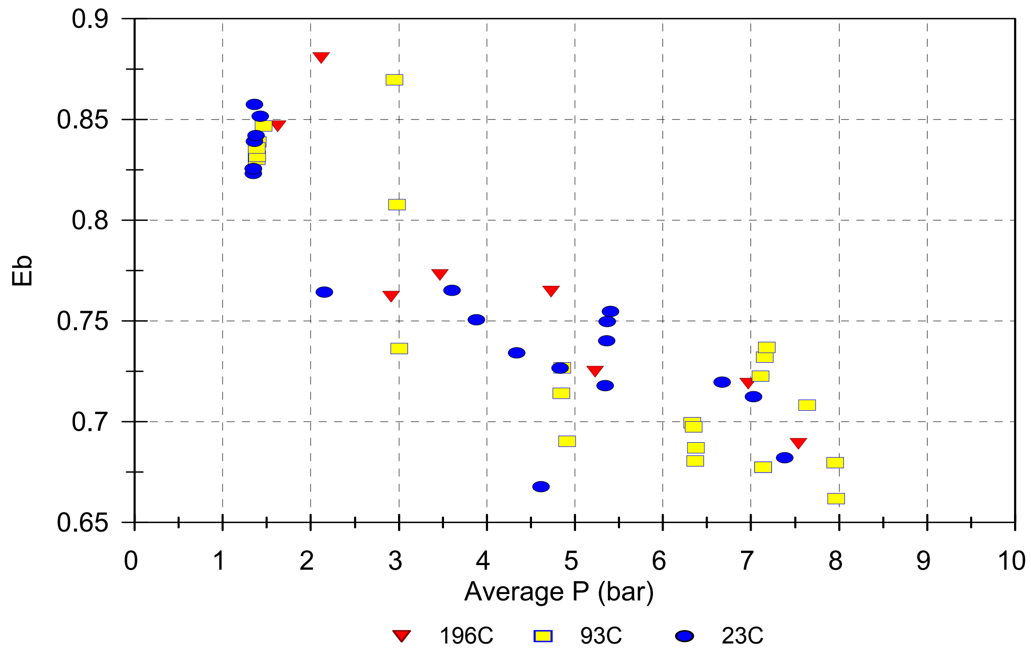

Fig. B.5. Membrane efficiency vs average pressure: Membrane 1226678-1-1, 25% Ar in He.

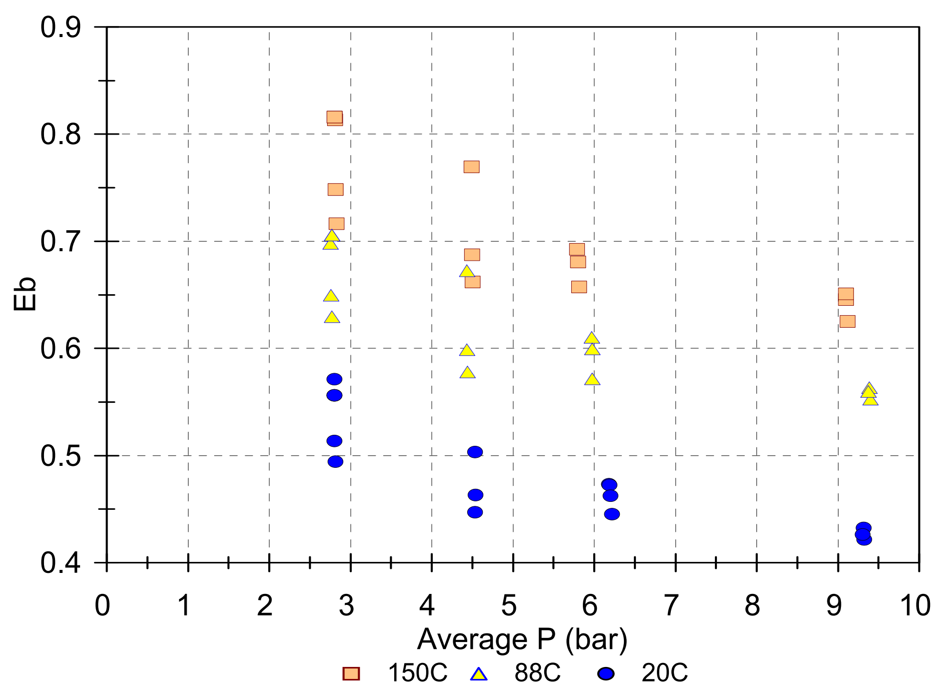

Fig. B.6. Membrane efficiency vs average pressure: Membrane 1230530-89, 25% CH_4 in H_2.

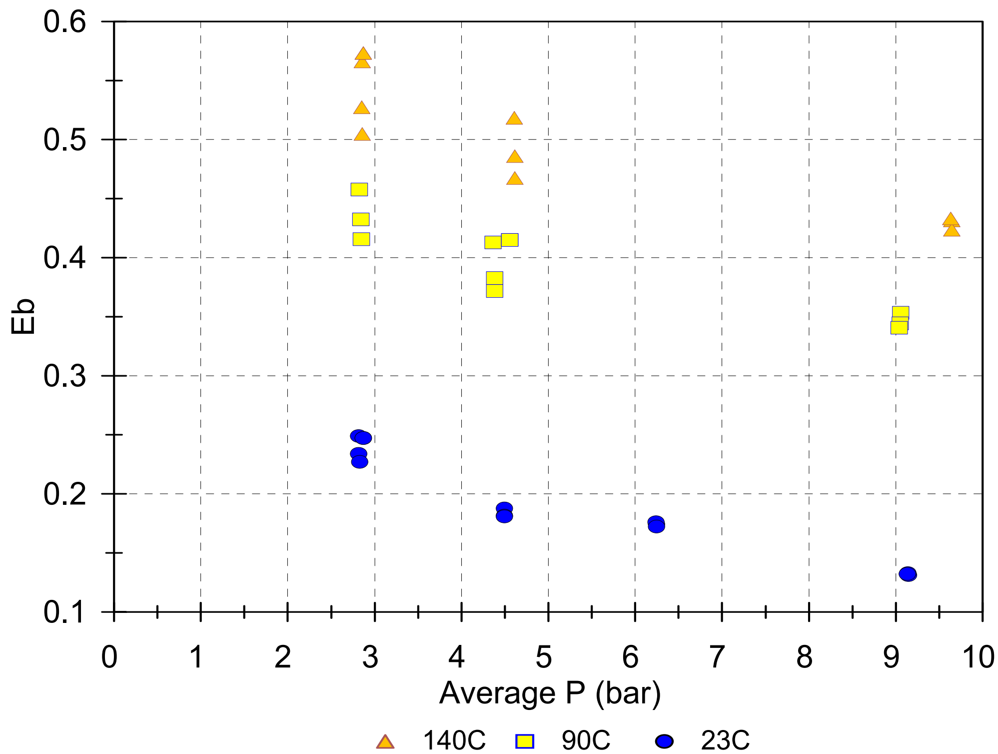

Fig. B.7. Membrane efficiency vs average pressure: Membrane 1230530-89, 25.02% C_2H_6 in H_2.

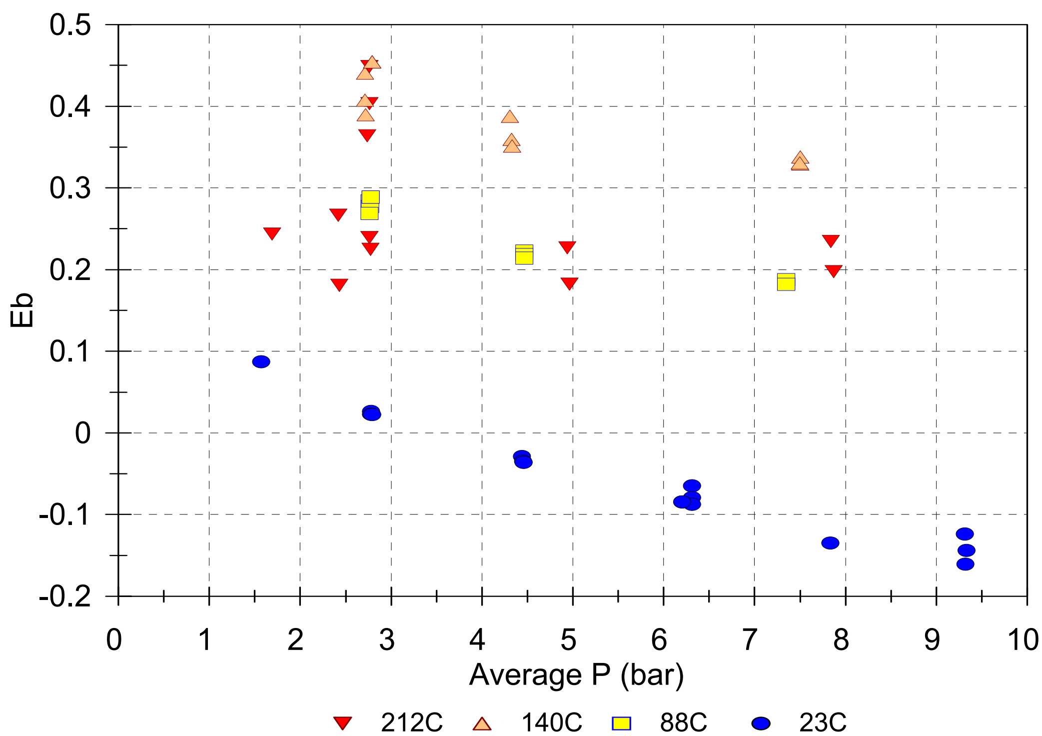

Fig. B.8. Membrane efficiency vs average pressure: Membrane 1230530-89, 24.97% C_3H_8 in H_2.

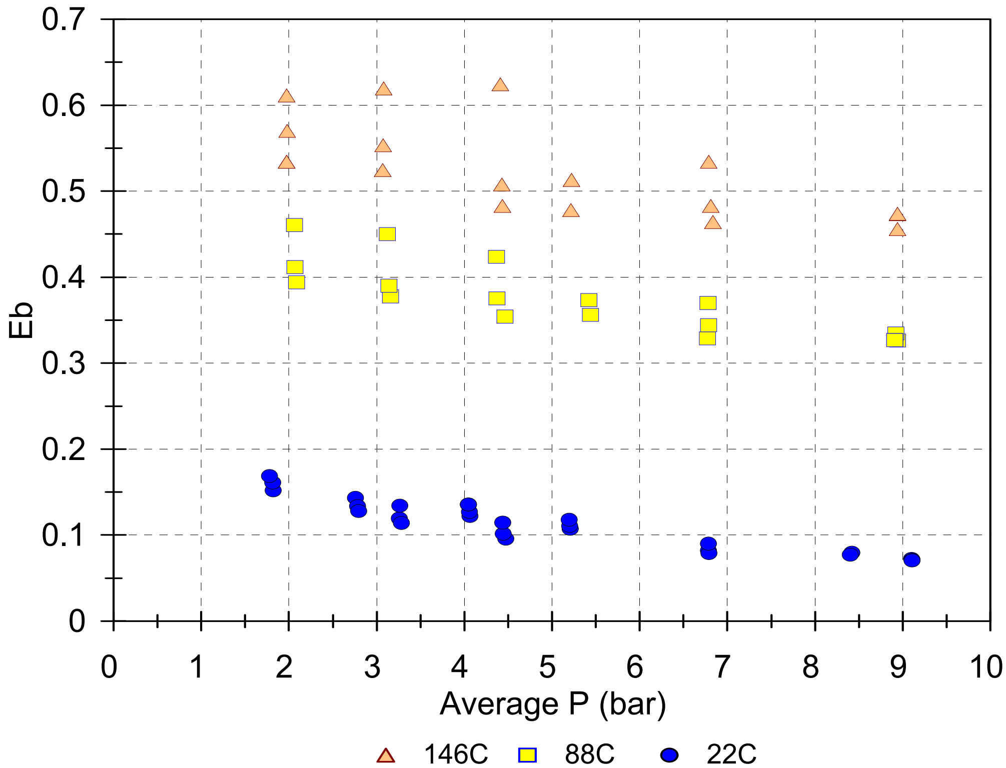

Fig. B.9. Membrane efficiency vs average pressure: Membrane 1230530-89, 25% CO_2 in He.

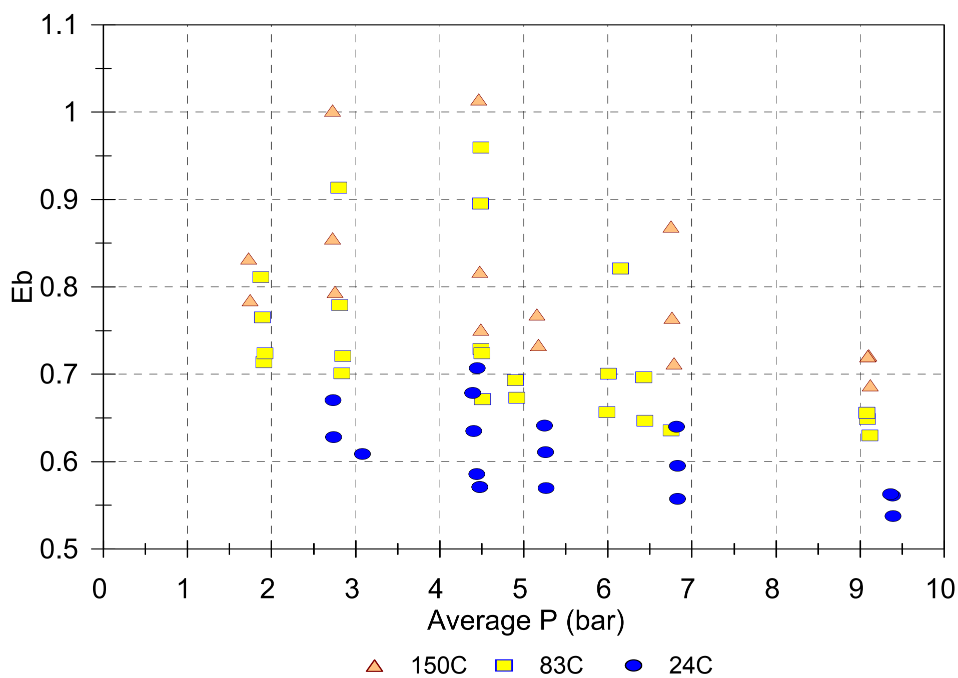

Fig. B.10. Membrane efficiency vs average pressure: Membrane 1230530-89, 25% Ar in He.

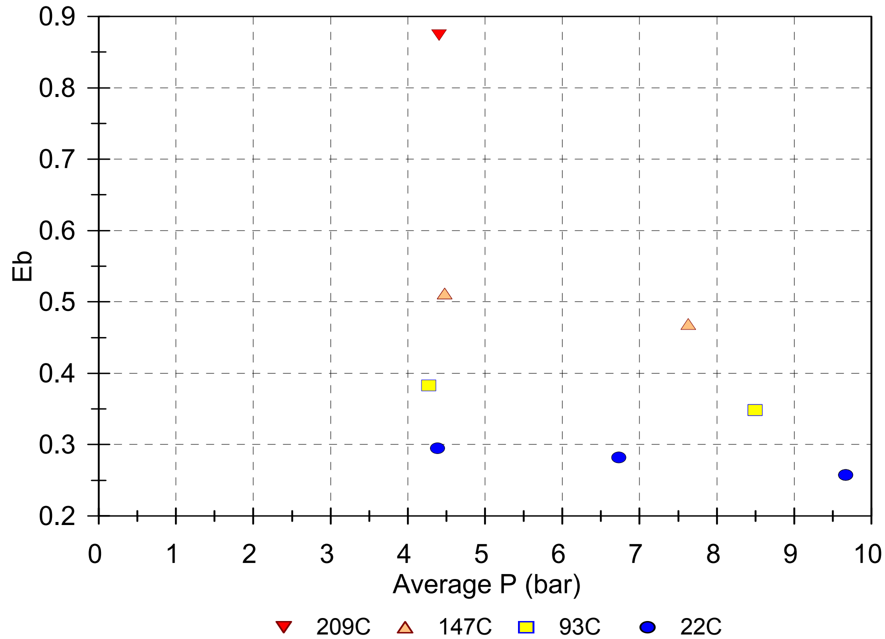

Fig. B.11. Membrane efficiency vs average pressure: Membrane 1230530-108, 25% CH_4 in H_2.

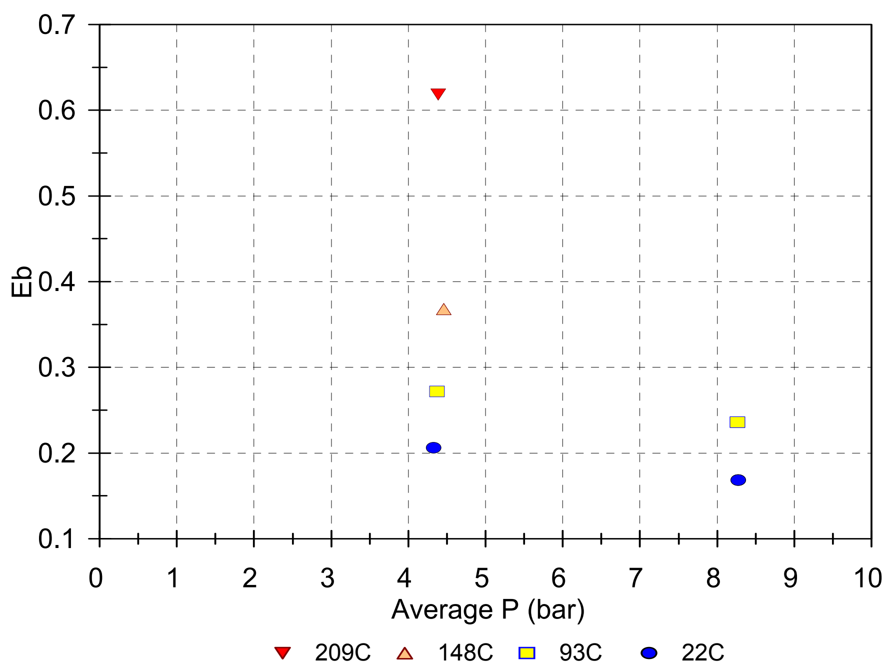

Fig. B.12. Membrane efficiency vs average pressure: Membrane 1230530-108, 25.02% C_2H_6 in H_2.

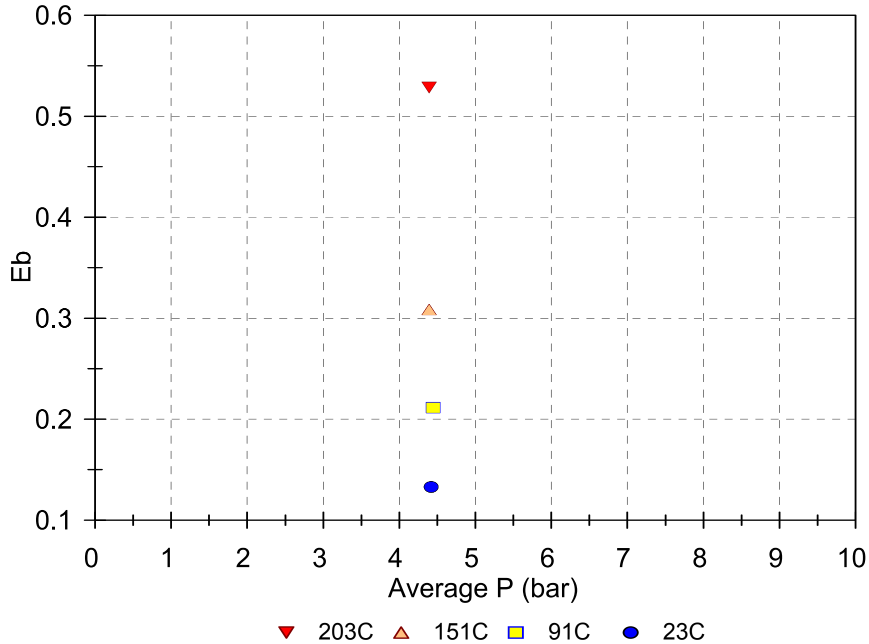

Fig. B.13. Membrane efficiency vs average pressure: Membrane 1230530-108, 24.97% C_3H_8 in H_2.

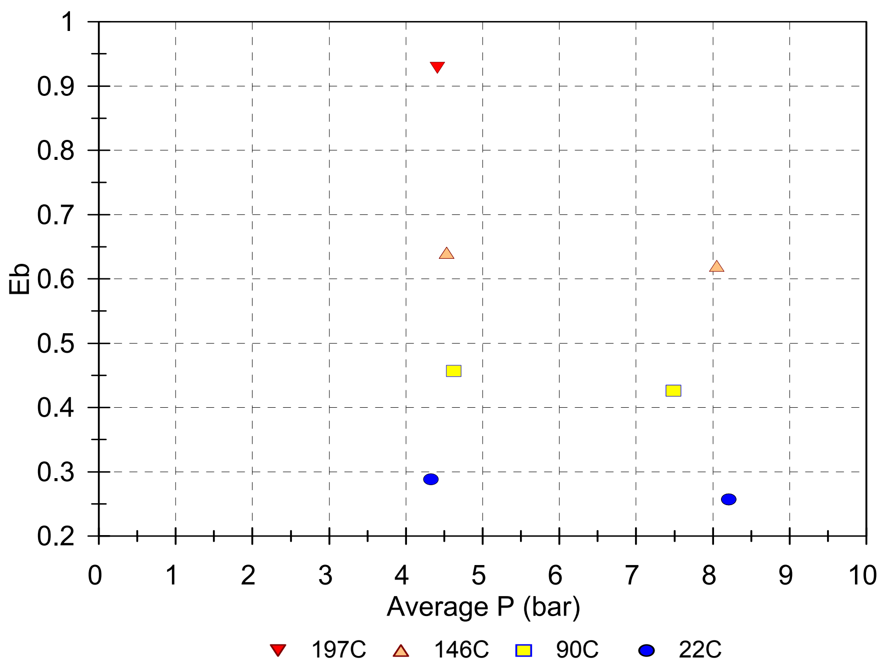

Fig. B.14. Membrane efficiency vs average pressure: Membrane 1230530-108, 25% CO_2 in He.

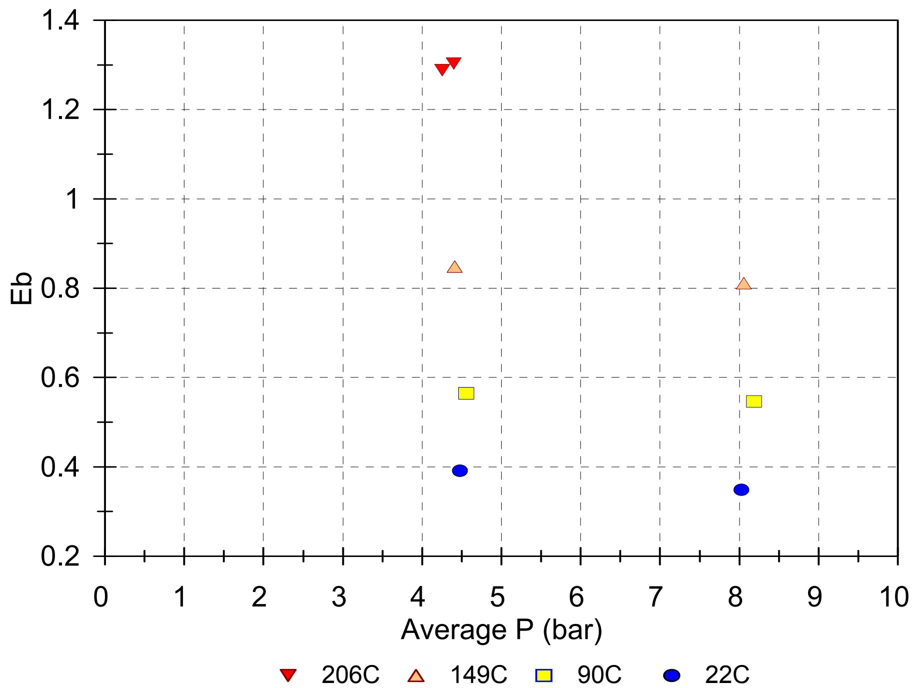

Fig. B.15. Membrane efficiency vs average pressure: Membrane 1230530-108, 25% Ar in He.

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